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Coastal and Hydraulics Laboratory

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Coast of South Carolina Storm Surge Study

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Preface

This report describes procedures followed and results obtained for a two-phase investigation of storm-generated water levels along the open coast and up the major tributaries of South Carolina. In the first phase, tropical and extratropical storm events that have historically impacted South Carolina are simulated using the long-wave hydrodynamic model ADCIRC. The resulting storm surge elevations with corresponding tides are then analyzed to develop combined event stage versus frequency-of-occurrence relationships for 38 selected locations within the study area. The second phase of the study generates frequency-indexed storm surge hydrographs for a separate modeling effort involving the Santee River Flood Control Project. This study was performed by the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL) for the U.S. Army Engineer District, Charleston (CESAC).

The investigation reported herein was conducted by Dr. Norman W. Scheffner, research hydraulic engineer, CHL. Mr. Fulton C. Carson, computer scientist, CHL, contributed significantly to the study by developing the bathymetric and topographic database and installing these data into the computational grid. The study was initiated in January 2000 and completed in May 2000. Ms. Sara Brown, Technical Services Division, Design Hydraulics Branch, Charleston District, was the study manager and point of contact. The study was performed under the general supervision of Dr. James R. Houston and Mr. Thomas W. Richardson, former Director and Acting Director, CHL.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and Mr. Armando J. Roberto, Jr., was Acting Commander.

1 Introduction

The U.S. Army Engineer District, Charleston, requested the Coastal and Hydraulics Laboratory of the U.S. Army Engineer Research and Development Center (ERDC) to conduct a two-phase storm surge investigation for the state of South Carolina. The first phase performed a storm surge frequency analysis for the open coast and major tidal tributaries of the state. The second part of the study used the generated frequency relationships to develop frequency-indexed storm surge hydrograph boundary conditions for the computational boundary of the Resource Management Associates (RMA) model used in the Santee River Flood Control Project. This report provides documentation of the procedures followed and results obtained for the study.

The open coast of South Carolina shown in Figure 1 extends approximately 297.72 km (185 miles) northeast from Savannah, GA to about 136.79 km (85 miles) west of Wilmington, NC. The northern portion of the

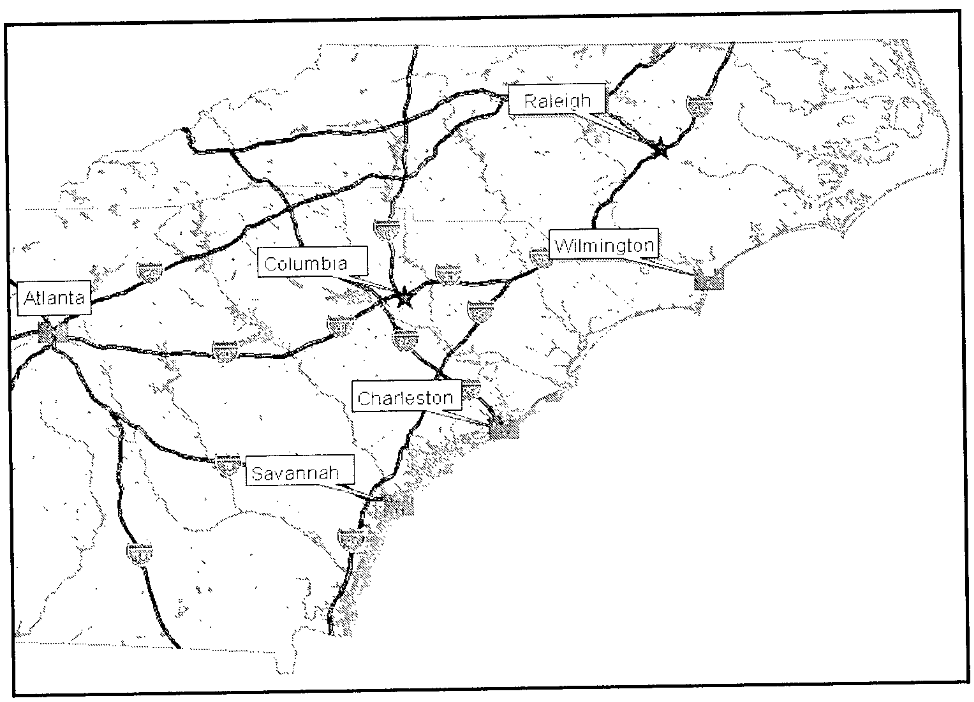

Figure 1. South Carolina study area

state is open coast; however, the middle and southern portions are characterized with barrier islands and extensive tidal flat areas. Because of these tidal marsh regions, the numerical model used to simulate surge must be capable of simulating wetting and drying of computational elements.

The storm surge simulations for this study were computed using the ADCIRC (ADvanced CIRCulation) long-wave hydrodynamic model (Leuttich, Westerink, and Scheffner 1992). The ADCIRC model solves the depth-averaged Generalized Wave Continuity Equation (GWCE) formulation of the governing equations and has been extensively applied to projects requiring frequency analysis of storm events. The general methodology developed for these previous studies is applied to the present investigation.

The computation of frequency-of-occurrence relationships is based on results of a statistical procedure known as the Empirical Simulations Technique (EST) (Scheffner et al. 1999). The EST simulates life-cycle sequences of nondeterministic multiparameter systems such as storm events and their corresponding environmental impacts. The approach is based on a "bootstrap" resampling-with-replacement, interpolation, and subsequent smoothing technique in which random sampling of a finite length database is used to generate a larger database. This procedure is repeated to generate a large population of life-cycle databases. These multiple databases of storm activity are postprocessed to compute mean value frequency relationships with standard deviation error estimates.

The mean value frequency relationships are then used to select historic events which can be scaled in magnitude to represent 2-, 25-, 50-, 100-, and 500-year return period storms. Hydrographs for these events are archived at locations corresponding to the open ocean boundary of the RMA hydrodydnamic model used in the Santee River Flood Control Project.

The present study requires completion of three sequential modeling tasks. Detailed description of each task is provided in the following sections: (a) the ADCIRC model, (b) the EST model, and (c) computation of frequency-indexed boundary condition hydrographs for the RMA model. Documentation of the various components of the study is followed by a summary and conclusions.

2 Advanced Circulation Model

In the following sections, documentation for the hydrodynamic model is given, followed by a description of the computational grid developed for the South Carolina study. Verification of the model by comparison to both tidal elevation data and storm surge data is provided to demonstrate that the model is capable of simulating realistic surface elevations for historical storm events for which measured surge data are available.

Model Documentation

Water-surface elevations and currents for both tides and storm events are obtained from the large-domain long-wave hydrodynamic ADCIRC model (Luettich, Westerink, and Scheffner 1992). The ADCIRC model is an unstructured grid finite-element long-wave model developed under the U.S. Army Corps of Engineers (USACE) Dredging Research Program (DRP) (Griffis et al. 1995). The model was developed as a family of two- and three-dimensional codes with the capability of:

a. Simulating tidal circulation and storm surge propagation over large computational domains while simultaneously providing high resolution in areas of complex shoreline and bathymetry. The targeted areas of interest include continental shelves, nearshore areas, and estuaries.

b. Representing all pertinent physics of the three-dimensional equations of motion. These include tidal potential, Coriolis effect, and all nonlinear terms of the governing equations.

c. Providing accurate and efficient computations over time periods ranging from months to years.

In two dimensions, model formulation begins with the depth-averaged shallow-water equations for conservation of mass and momentum subject to incompressibility and hydrostatic pressure approximations. The

Boussinesq approximation, where density is considered constant in all terms but the gravity term of the momentum equation, is also incorporated into the model. Using the standard quadratic parameterization for bottom stress and omitting baroclinic terms and lateral diffusion and dispersion, the following set of conservation statements in primitive, nonconservative form and expressed in a spherical coordinate system are incorporated into the model (Flather 1988; Kolar et al. 1994):

$$\frac{\partial \zeta}{\partial t} + \frac{1}{R\cos\phi}\left[\frac{\partial UH}{\partial \lambda} + \frac{\partial (UV\cos\phi)}{\partial \phi}\right] = 0 \tag{1}$$

$$\frac{\partial U}{\partial t} + \frac{1}{r\cos\phi}U\frac{\partial U}{\partial \lambda} + \frac{1}{R}V\frac{\partial U}{\partial \phi} - \left(\frac{\tan\phi}{R}U + f\right)V =$$
$$-\frac{1}{R\cos\phi}\frac{\partial}{\partial \lambda}\left[\frac{P_s}{\rho_0} + g(\zeta - \eta)\right] + \frac{\tau_{s\lambda}}{\rho_0 H} - \tau_* U \tag{2}$$

$$\frac{\partial V}{\partial t} + \frac{1}{r\cos\phi}U\frac{\partial V}{\partial \lambda} + \frac{1}{R}V\frac{\partial V}{\partial \phi} - \left(\frac{\tan\phi}{R}U + f\right)U =$$
$$-\frac{1}{R\cos\phi}\frac{\partial}{\partial \phi}\left[\frac{P_s}{\rho_0} + g(\zeta - \eta)\right] + \frac{\tau_{s\lambda}}{\rho_0 H} - \tau_* V \tag{3}$$

where t represents time, λ and ϕ are degrees longitude (east of Greenwich is taken positive) and degrees latitude (north of the equator is taken positive), η is the free-surface elevation relative to the geoid, U and V are the depth-averaged horizontal velocities, R is the radius of the earth, $H = \zeta + h$ is the total water column depth, h is the bathymetric depth relative to the geoid, $f = 2\Omega \sin \varphi$ is the Coriolis parameter, Ω is the angular speed of the earth, p_s is the atmospheric pressure at the free surface, g is the acceleration due to gravity, η is the effective Newtonian equilibrium tide potential, ρ_0 is the reference density of water, $\tau_{s\lambda}$ and $\tau_{s\varphi}$ are the applied free-surface stress, and τ_* is given by the expression $C_f\,(U^2 + V^2)^{1/2}/H$ where C_f equals the bottom friction coefficient which can be specified as either linear or nonlinear (Luettich, Westerink, and Scheffner 1992).

The momentum equations (Equations 2 and 3) are differentiated with respect to λ and t and substituted into the time-differentiated continuity equation (Equation 1) to develop the following Generalized Wave Continuity Equation (GWCE):

$$
\begin{aligned}
&\frac{\partial^2 \zeta}{\partial t^2} + \tau_0 \frac{\partial \zeta}{\partial t} - \frac{1}{R\cos\phi}\frac{\partial}{\partial \lambda}\left[\frac{1}{R\cos\phi}\left(\frac{\partial(HUU)}{\partial \lambda} + \frac{\partial(HUV\cos\phi)}{\partial \phi}\right) - UVH\frac{\tan\phi}{R}\right] \\
&\left[-2\omega\sin\phi HV + \frac{H}{R\cos\phi}\frac{\partial}{\partial \lambda}\left(g(\zeta - \alpha\eta) + \frac{P_s}{\rho_0}\right) + \tau_* HU - \tau_0 HU - \frac{\tau_{s\lambda}}{\rho_0}\right] \\
&-\frac{1}{R}\frac{\partial}{\partial \phi}\left[\frac{1}{R\cos\phi}\left(\frac{\partial(HVV)}{\partial \lambda} + \frac{\partial(HVV\cos\phi)}{\partial \phi}\right) + UUH\frac{\tan\phi}{R} + 2\omega\sin\phi HU\right] \\
&-\frac{1}{R}\frac{\partial}{\partial \phi}\left[\frac{H}{R}\frac{\partial}{\partial \phi}\left(g(\zeta - \alpha\eta) + \frac{P_s}{\rho_0}\right) + (\tau_* - \tau_0)HV - \frac{\tau_{s\phi}}{\rho_0}\right] \\
&-\frac{\partial}{\partial t}\left(\frac{VH}{R}\tan\phi\right) - \tau_0\left(\frac{VH}{R}\tan\phi\right) = 0 \qquad (4)
\end{aligned}
$$

The ADCIRC-2DDI model solves the GWCE (Equation 4) in conjunction with the primitive momentum equations given in Equations 2 and 3.

The ADCIRC model solves the governing equations with a finite-element algorithm over arbitrary bathymetry encompassed by irregular sea and shore boundaries. This algorithm allows for flexible spatial discretizations over the entire computational domain and has demonstrated robust stability characteristics. The advantage of this flexibility in developing a computational grid is that larger elements can be specified in the open-ocean regions where less resolution is needed, whereas smaller elements can be applied in the nearshore and estuary areas where finer resolution is required to resolve hydrodynamic details.

Accurate modeling of storm surge propagation across the barrier islands and tidal flats of the southern portion of the study area requires a capability of wetting and drying of computational cells. An element-based technique for wetting/drying was developed for implementation in ADCIRC. Conceptually, the algorithm assumes removable barriers exist along the sides of all triangular elements of the grid. Nodes of the elements are designated as "dry" nodes, "interface" nodes, and "wet" nodes. All elements connected to a dry node are assumed to have barriers in place in which there is no flow through the element, i.e., a dry element. An element connected to all wet nodes is a wet element and included in the full-flow domain. Interface nodes connect wet and dry elements. Boundaries connecting interface nodes are considered as standard land boundary nodes at which the water level rises and falls against the element barrier.

Computational Grid

A problem often encountered in the modeling of nearshore flow dynamics is that the computational boundaries of the model are not well removed from the area of interest. For example, the continental shelf can substantially affect the amplitude and phase of a storm surge or tide propagating from open water onto the shelf. If the model boundary conditions are specified on the shelf, then boundary condition errors are introduced into the solution because the assumed boundary conditions are posed in a dynamic flow region, i.e., the transformation of the flow field over rapidly changing bathymetry. An advantage for the use of large domains is that boundary conditions can be defined in deep water where nonlinear influences of the continental shelf are minimal. This approach to specification of boundary conditions virtually eliminates contamination of model results from poorly defined boundary conditions.

The 20,000-node computational domain (shown in Figure 2) used in the generation of the DRP East Coast, Gulf of Mexico, and Caribbean Sea tidal database formed the initial grid for this study because the tidal boundary

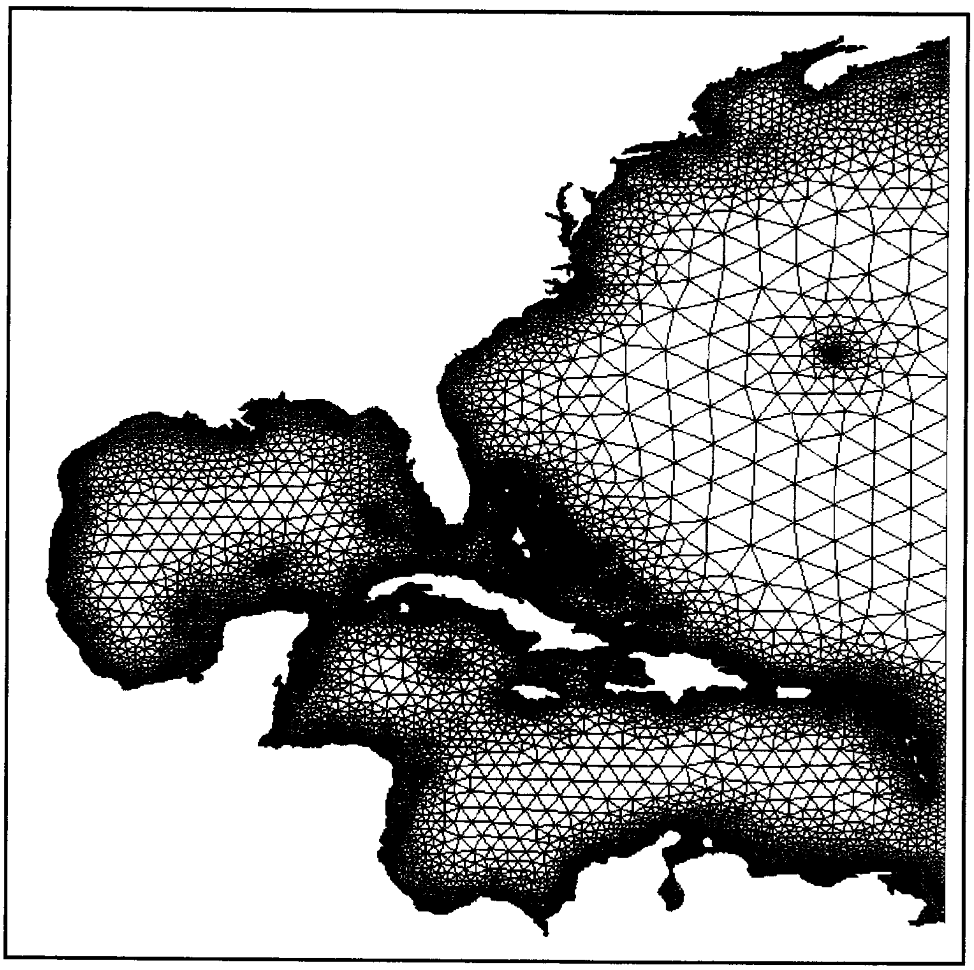

Figure 2. The DRP East Coast, Gulf of Mexico, Caribbean Sea grid

conditions along the eastern boundary (long. 60° W) had already been determined (Westerink, Luettich, and Scheffner 1993). Additionally, proper flow connectivity between the Gulf of Mexico, Caribbean Sea, and the South Atlantic Bight was assured because the proper bathymetry of all basins had already been established. For example, by modeling the entire domain, the flow and surge distribution resulting from hurricanes moving toward the study area from the Caribbean Sea or Gulf of Mexico is properly simulated. Minimum node-to-node spacing of this initial grid was on the order of 5 km. Minimum resolution along the open coast and up the major tributaries of the study area was decreased to approximately 700 m to provide sufficient detail of the local bathymetry and topography. The increased resolution of the study area is shown in Figure 3 with Figure 4 showing the nearshore bathymetry.

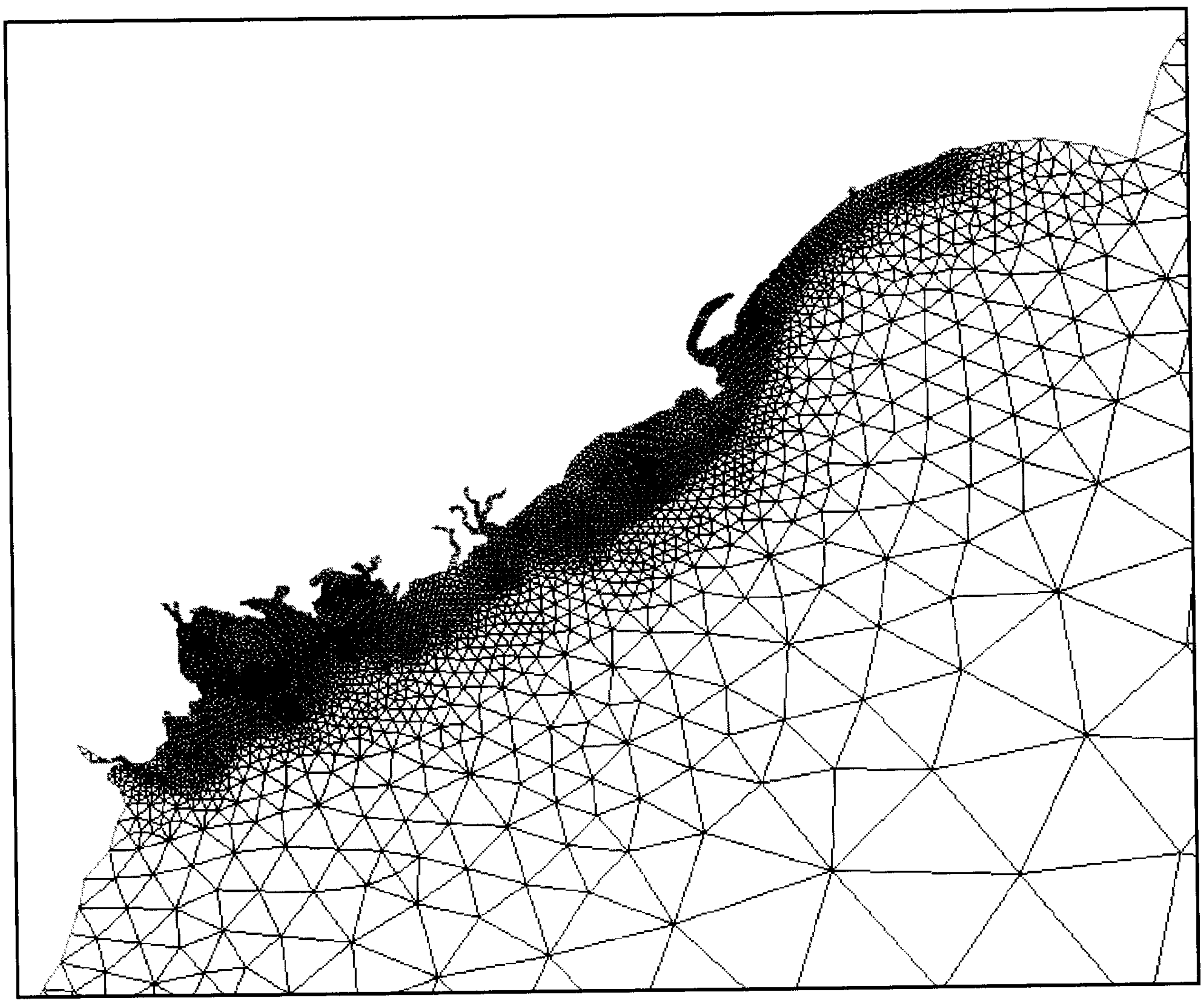

Figure 3. Grid resolution in the study area

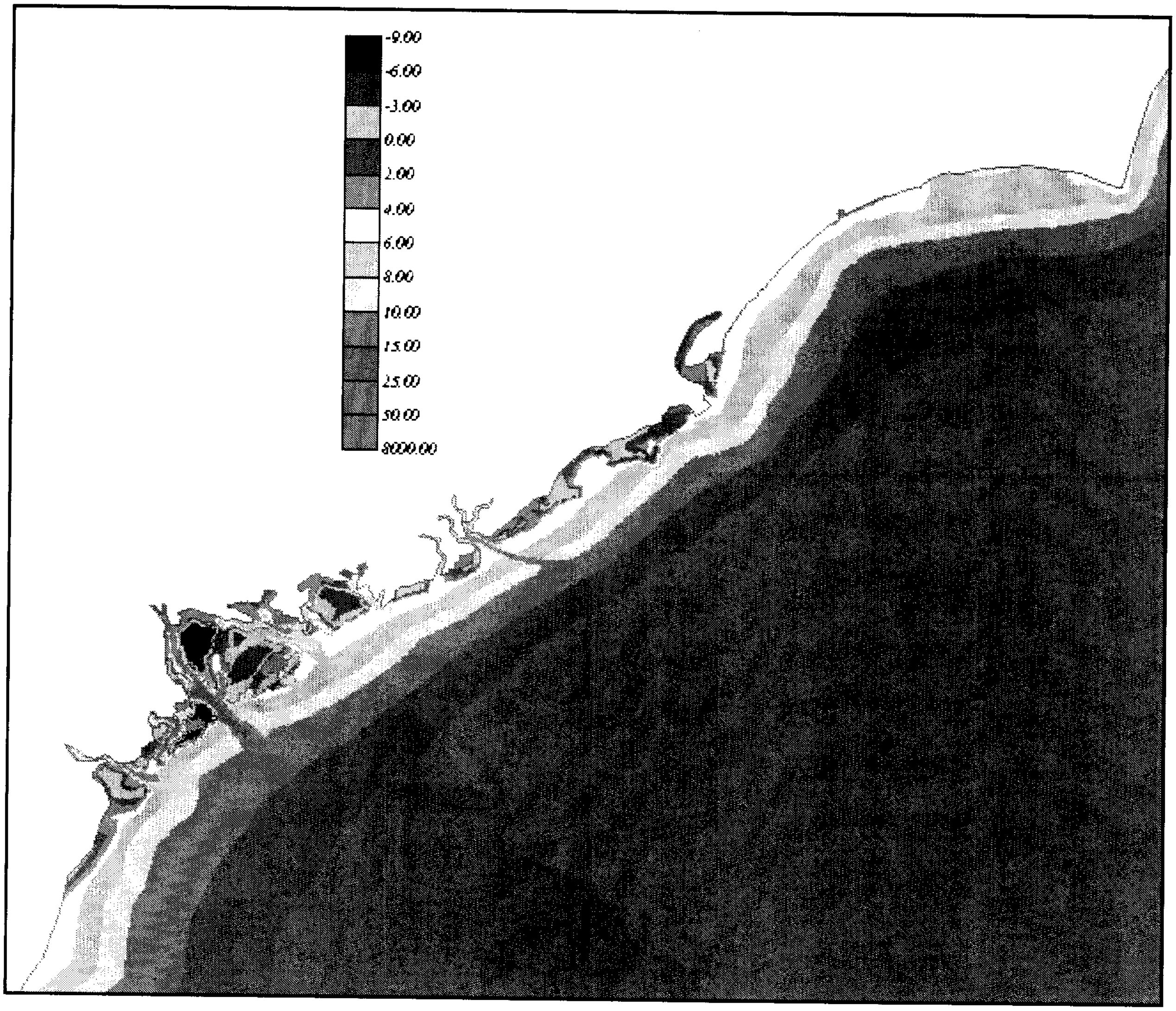

Figure 4. Bathymetry in the study area

Tidal and storm surge water-surface elevation data computed with the ADCIRC model were archived at 38 stations for subsequent computation of frequency-of-occurrence relationships. These locations, provided by the Charleston District, are listed in Table 1 and shown in Figure 5.

Table 1. Station/Locations			
	East Longitude	North Longitude	Station Location
1	-80.88690	32.03502	Savannah River
2	-80.83353	32.12085	Calibogue Sound
3	-80.82016	32.47138	Broad River
4	-80.75940	32.53786	Whale Branch
5	-80.67868	32.36861	Beaufort River
6	-80.65256	32.25505	Port Royal Sound
7	-80.61955	32.50939	Coosaw River
8	-80.58289	32.28718	Trenchards Inlet
9	-80.54001	32.54247	Combahee River
10	-80.50353	32.59817	Ashepoo River
11	-80.45977	32.33613	Fripp Inlet
12	-80.45696	32.47208	St. Helena Sound
13	-80.40225	32.63872	Upper North Edisto
14	-80.35598	32.48759	South Edisto
15	-80.18945	32.56440	North Edisto
16	-80.17559	32.59805	Bohicket Creek
17	-80.05566	32.77747	Upper Stono River
18	-79-99170	32.83528	Ashley River
19	-79.99020	32.62412	Stono River
20	-79.96354	32.88877	Cooper River
21	-79.91779	32.76700	Charleston Inner Harbor
22	-79.87134	32.86977	Wando River
23	-79.85783	32.75057	Charleston Harbor
24	-79.72581	32.82424	Dewees Inlet
25	-79.56516	33.00480	Bulls Bay
26	-79.41609	33.05850	Cape Romain Refuge
27	-79.28091	33.35109	Sampit River
28	-79.27849	33.11797	South Santee
29	-79.24243	33.14258	North Santee
30	-79.24110	33.43211	Black River
31	-79.18141	33.20379	Winyah Bay
32	-79.16491	33.32672	North Inlet
33	-79.16424	33.45711	Waccamaw River
34	-79.13960	33.39780	Pawleys Inlet
35	-79.11064	33.44661	Midway Inlet
36	-79.03273	33.52889	Murells Inlet
37	-78.80144	33.77483	AIWW Horry County
38	-78.54868	33.84866	Little River3

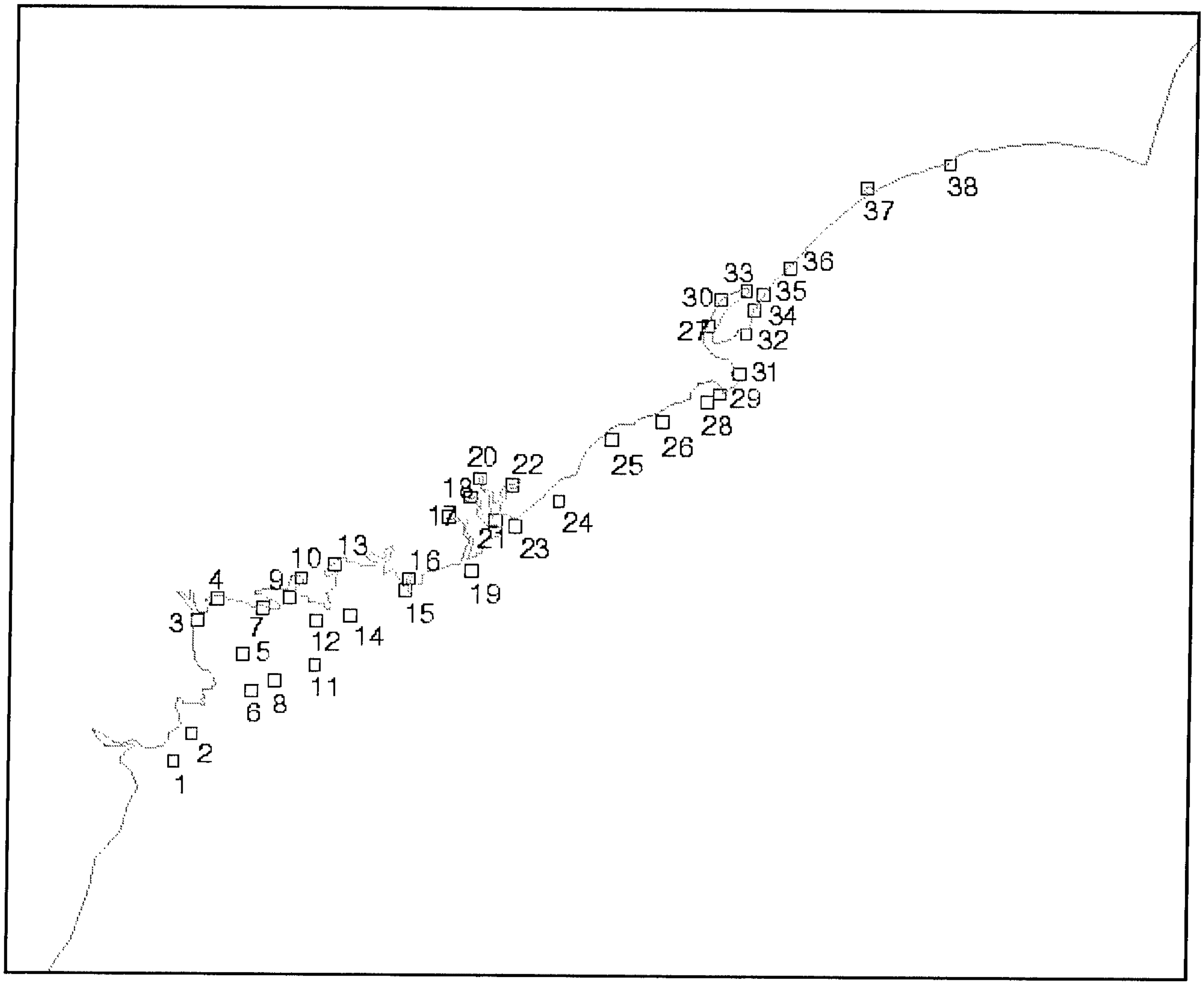

Figure 5. Study area data/frequency station locations

Verification of ADCIRC Model

Verification of the hydrodynamic model is initially required to assure that grid resolution, bathymetry, and boundary conditions are adequately prescribed to acceptably reproduce known or observed events. For the case of tides, verification is made to an eight-constituent tidal time series signal reconstructed from published International Hydrographic Office (IHO) tidal constituents (IHO 1991). For storm events, verification is achieved by comparing computed surface-elevation maximum surge values to published surge data. The following two sections describe the tidal and storm verification effort.

Tidal propagation

The ADCIRC model was initially verified for tides during the DRP with the generation of a tidal constituent database for the domain shown in Figure 2. However, to insure that the increased resolution grid with associated bathymetry have not had adverse effects on the initial calibration, a verification check was made. This comparison was made for the Savannah River and Charleston Inner Harbor tidal stations for which IHO data are available.

Tidal propagation is simulated within ADCIRC by specifying a surface-elevation time series on the eastern boundary of the computational grid of Figure 2. This is accomplished by reconstructing an eight-constituent (M_2, S_2, N_2, N_1, K_1, O_1, Q_1, and P_1) tidal elevation time series at each boundary node based on amplitudes and Greenwich epoch values obtained from the existing DRP tidal database. Additionally, tidal potential terms are specified at each node of the computational grid. The ADCIRC model has an internal harmonic analysis option in which individual constituent amplitudes and epochs are computed at user specified locations during the tidal simulation. Verification of the tide was made by comparing ADCIRC computed amplitudes and local epochs at the Savannah River and Charleston Inner Harbor tide gage locations to the corresponding IHO amplitude and local epoch values. Comparisons of ADCIRC versus IHO constituent amplitudes and local epochs (κ) are shown in Table 2.

Table 2. Tidal Verification of ADCIRC

	Savannah River Tidal Station				Charleston Inner Harbor Tidal Station			
	Amplitude — m		Local Epoch κ		Amplitude — m		Local Epoch κ	
Constituent	ADCIRC	IHO	ADCIRC	IHO	ADCIRC	IHO	ADCIRC	IHO
M_2	0.9400	0.9950	199.12	232.90	0.7854	0.7430	205.73	226.90
S_2	0.1050	0.1790	204.64	253.80	0.0812	0.1290	208.97	248.80
N_2	0.1847	0.2160	181.13	218.60	0.1570	0.1640	188.10	216.60
K_1	0.1067	0.1030	107.10	126.70	0.1004	0.1050	105.99	126.70
O_1	00.079	0.0800	006.61	138.20	0.0742	0.0760	111.12	136.20
Q_1	0.0149	0.0150	107.38	141.90	0.0140	0.0150	106.33	138.90
P_1	0.0418	0.0370	104.14	123.10	0.0376	0.0340	103.17	127.10
K_2	0.0231	0.0530	284.36	261.40	0.0194	0.0320	271.84	241.40

Comparison results are considered acceptable. For example, the percent ratio of ADCIRC/IHO amplitude for the M_2 constituent at Savannah River and Charleston Inner Harbor is 94.5 percent and 105.7 percent respectively. Phasing for ADCIRC is 33.8 and 21.2 deg earlier than the IHO database for the Savannah River and Charleston Inner Harbor gages, respectively. Accuracy of phasing can be computed by noting that the speed of the M_2 constituent is 28.984 percent/hr (period of 12.421 hr), therefore the M_2

constituent arrival time is approximately 1 hr early for the two test locations. For the purpose of this investigation, this is acceptable. To demonstrate a qualitative comparison between the ADCIRC and IHO results, Figures 6 and 7 show comparisons of reconstructed tidal signals based on the ADCIRC harmonic analysis of tides at the two stations and the IHO database. As shown, the simulation provides sufficient accuracy to satisfy the goals of the present study. Therefore, the conclusion is that the model and associated grid are verified for tides, and computed tidal constituents can be used in the frequency analysis to be described later in this report.

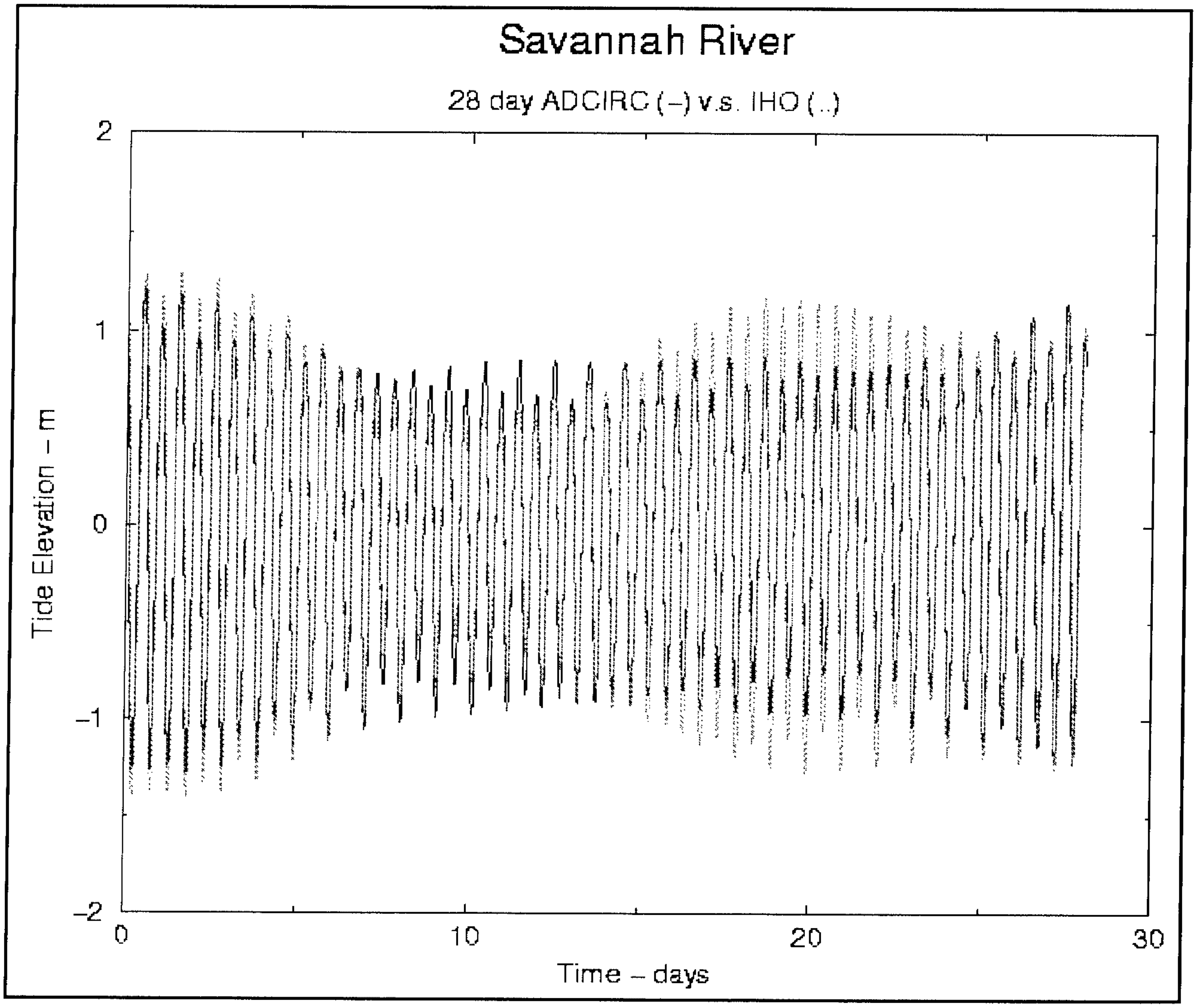

Figure 6. Comparison of ADCIRC and IHO reconstructed tide at Savannah River

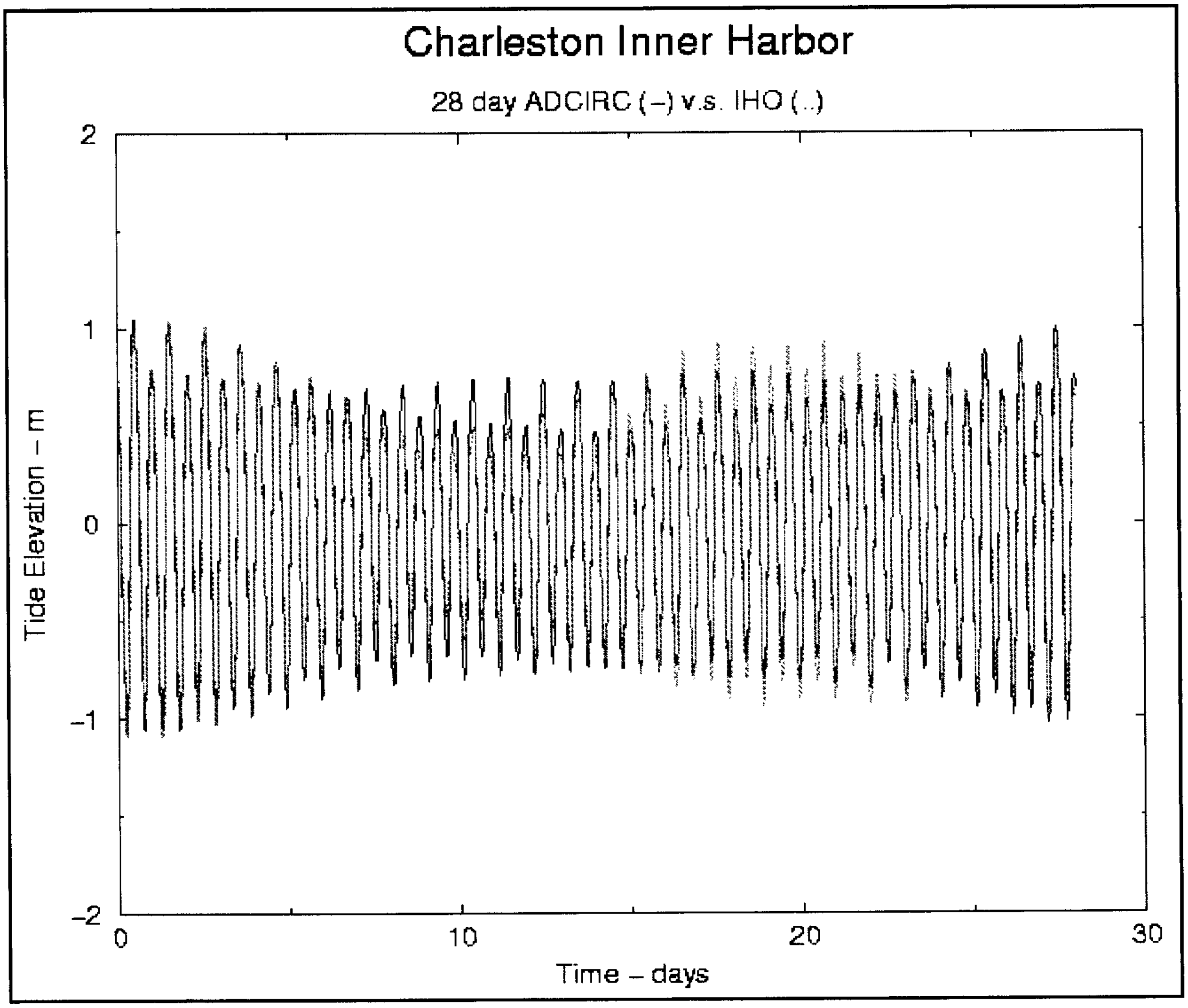

Figure 7. Comparison of ADCIRC and IHO reconstructed tide at Charleston Inner Harbor

Tropical storm surge

The hurricane wind field model used in conjunction with the ADCIRC model is the Hurricane Planetary Boundary Layer (PBL) model developed by Cardone (Cardone, Greenwood, and Greenwood 1992). This model simulates hurricane-generated wind and atmospheric pressure fields by solving the equations of horizontal motion which have been vertically averaged through the depth of the planetary boundary layer. Additionally, a moving coordinate system is defined so its origin always coincides with the moving low-pressure center of the eye of the storm p_c. Therefore, the standard equations of motion are transformed into the following relationships in Cartesian coordinates:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-fv=\frac{1}{\rho}\frac{\partial p_c}{\partial x}+\frac{\partial}{\partial x}\left[K_H\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)\right]+\frac{C_D}{h}|V|u \tag{5}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+fu=\frac{1}{\rho}\frac{\partial p_c}{\partial y}+\frac{\partial}{\partial y}\left[K_H\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)\right]+\frac{C_D}{h}|V|v \tag{6}$$

where (u,v) are the wind speeds in (x,y) directions, ρ is the mean air density, p_c is the pressure field representing the tropical cyclone, K_H is the horizontal eddy viscosity coefficient, C_D is the drag coefficient, h is the depth of the planetary boundary layer, and V is the magnitude of the wind velocity. The model includes parameterizations of the momentum, heat, and moisture fluxes together with surface drag and roughness formulations.

An exponential pressure law is used to generate a circularly symmetric pressure field situated at the low-pressure center of the storm:

$$p_c(r)=p_0+\Delta p e^{-(R/r)} \tag{7}$$

where p_0 is the pressure at the center or eye of the storm, $\Delta p = p - p_0$ is the pressure anomaly with p taken as an average background or far field pressure, R is the scale radius, often assumed equivalent to the radius to maximum wind, and r is the radial distance outward from the eye of the storm.

$$\frac{\tau_x}{\rho_0}=C_D\frac{\rho_{air}}{\rho_0}|V|u \tag{8}$$

and

$$\frac{\tau_y}{\rho_0}=C_D\frac{\rho_{air}}{\rho_0}|V|v \tag{9}$$

where τ_x, τ_y are the wind stresses in the x and y directions, respectively, $\rho_{air}/\rho_0 = 0.001293$ is the ratio of the air density to the average density of seawater, and C_D is the frictional drag coefficient. Both the ratio of air densities and the drag coefficient are assumed constant.

The Planatary Boundary Layer (PBL) model requires a series of input snapshots consisting of a set of meteorological parameters defining the storm at various stages of development or at particular times during its life.

These parameters include: latitude and longitude of the eye of the storm; track direction and forward speed measured at the eye; radius to maximum winds; central and peripheral atmospheric pressures; and an estimate of the geostrophic wind speed and direction. The radius to maximum winds is approximated using a nomograph that incorporates the maximum wind speed and atmospheric pressure anomaly (Jelesnianski and Taylor 1973). Peripheral atmospheric pressures were assumed equal to the standard atmospheric pressure of 1,013 millibars (mb) and the geostrophic wind speeds were specified as 6 knots in the same direction as the moving eye of the storm. The PBL model input consists of histogram and snapshot files which define the hourly location in latitude and longitude of the eye of the storm and the storm intensity parameters specified at defined times.

The PBL model computes a stationary wind and pressure field distribution corresponding to the storm characteristics specified in the snapshot file at locations corresponding the locations of the eye specified in the histogram file. These wind and pressure files are defined on a nested grid composed of five subgrids. Each subgrid measures 21 by 21 nodes in the x- and y-directions with the center of all subgrids defined at the eye of the hurricane. Although the number of nodes composing each subgrid is the same, the spatial resolution is doubled for each successive grid. For this study, the center grid with the finest resolution has a Δx and Δy grid spacing of 5 km. Incremental distances for the remaining subgrids are 10, 20, 40, and 80 km. These fixed grids translate with the propagating storm as defined by the histogram file.

The hurricane translational motion is incorporated into PBL model calculations by adding the forward and rotational velocity vector components. A nonlinear blending algorithm is then incorporated to generate a nested grid field of wind and pressure for each hour during the life of the storm event. These hourly wind and pressure fields are then interpolated from the PBL nested grid onto the hydrodynamic model grid and subsequently stored for use by the ADCIRC model. Although the PBL model is idealized and modifications in stress are not made for changing sea state and/or landfall, surge results have been shown to produce model surge results that are generally within 0.15 m of measured storm surge values (Mark and Scheffner 1997; Scheffner et al. 1994).

Snapshot and histogram files are computed from data contained in the National Oceanic and Atmospheric Administration's (NOAA) National HUrricane Center's DATabase (HURDAT) of tropical storm events (Jarvinen, Neumann, and Davis 1988). This database contains descriptions of all hurricane, tropical storm, and severe tropical depressions which have occurred along the East Coast, Gulf of Mexico, and Caribbean Sea from 1886 to present. The database contains latitude and longitude locations of the eye of the hurricane with the corresponding central pressure and maximum wind speeds at 6-hr intervals.

Verification comparisons for tropical event propagation for the coast of South Carolina study were made to three sources of data. In the first, simulated surge only (no tide) elevations at Savannah River and Charleston were compared to observed data reported by Harris (1963). This source of data documents peak surge elevations along the east and Gulf of Mexico coasts of the United States for all major tropical events occurring from 1926 through 1961. Of these events, eight produced recorded surges at Savannah and/or Charleston. The second source of comparison is the post Hurricane Hugo data reported by Garcia, Jarvinan, and Schuck-Kolben (1990). Table 3 shows the comparison of the observed data and the ADCIRC-computed surge elevations in meters, mean sea level. Maximum surge differences between the ADCIRC simulations and observed data are less than 0.305 m (1.0 ft) at all locations with average differences of 0.091 m (0.3 ft) at Savannah River and -0.030 m (-0.1 ft) at Charleston Inner Harbor.

Table 3. Tropical Storm Surge Comparisons of ADCIRC Results Versus Observations

HURDAT #	Name of Storm	Date of Storm	Savannah River (m)		Charleston Inner Harbor (m)	
			ADCIRC	Observed	ADCIRC	Observed
292	No Name	Sep 1928	1.19	—	1.10	1.22
296	No Name	Sep 1928	0.46	—	0.73	0.55
440	No Name	Oct 1944	1.68	1.83	1.04	1.16
449	No Name	Sep 1945	1.07	1.07	1.04	1.28
541	Hazel	Oct 1954	0.46	—	0.58	0.49
562	Flossy	Sep 1956	0.37	0.46	0.64	0.40
589	Gracie	Sep 1959	0.52	0.64	2.53	2.26
597	Donna	Sep 1960	0.73	—	0.76	0.76
872	Hugo	Sep 1989	0.49	—	2.47	2.38

The third source of data are surge values reported by Myers (1975). In the Myers report, a surge only (no tide, runup, or setup) elevation of 2.53 m (8.3 ft) msl is reported for Hurricane Gracie at Charleston. This value is in agreement with the values reported in Table 3. Additional storm surge data are given by Myers. However the reported values represent high-water marks, i.e., combined surge, tide, setup, and runup. Although storm surge values generated by the ADCIRC model cannot be directly compared to high-water marks, some approximation can be made to allow for a comparison of simulated data to field measurements. For example, if peak surge is assumed to coincide with high tide and if offshore breaking waves are considered to be on the order of 4.57 m (15 ft) then approximations of a high-water mark can be made as follows. Tide can be computed from the DRP tidal database (Scheffner et al. 1994), wave setup can be approximated as 19 percent of the breaking wave height (Dean and Dalrymple

1984), and runup can be considered negligible for nonopen coast stations. If these approximations are made to the simulated peak surge values, then realistic comparisons to the observations reported in the NOAA technical report can be made. Selected events are the August 1911 (No. 196), August 1940 (No. 398), and Hurricane Hazel (No. 541) of October 1954. These comparisons are shown in Table 4. High-water marks for Hurricane No. 196 are reported for Charleston and for Hurricane No. 398 near Beaufort, SC. ADCIRC comparisons made at ADCIRC sta 21 (Charleston Inner Harbor) and 7 (Coosaw River) respectively. Data for Hurricane Hazel is shown for Holden Beach Bridge and Calabash, NC, with ADCIRC sta 38 (Little River) used for comparison. These comparisons are considered very good and are based on realistic approximations.

Table 4. High-Water Mark Comparisons for ADCIRC and Measured

Storm number, name, date	ADCIRC surge, m, msl	Tide, m, msl	Setup, m	High water mark, m, msl	NOAA high water mark, m, msl
196 - 8/1911	0.58	0.73	0.91	2.22	2.29
398 - 8/1940	2.07	0.85	0.91	3.83	4.33
541 - 10/1954	3.38	1.07	0.91	5.36	5.06

Conclusions

The ADCIRC model has been shown to satisfactorily reproduce tidal circulation and tropical storm surge elevations within the project area. For example, ADCIRC-generated surge values at the Savannah River and Charleston Harbor gages averaged within 0.025 m of measured peak storm surge values for nine historical events. Peak deviations between model and measurements were only +0.27 m and -0.24 m. Additionally, computed high-water mark values based on ADCIRC surge values agree to within 0.25 m of the NOAA measured values reported by Meyers (1975). This degree of model-to-measurement comparison is considered excellent and more than adequate to demonstrate that the ADCIRC model is capable of accurately modeling storm surge. This simulation capability will subsequently be used to generate a database of historical and historically based storm events for use in generating frequency-of-occurrence relationships at the stations listed in Table 1 and shown in Figure 5. The following section describes the statistical approach used to generate multiple life-cycle simulations of storm activity for the study area and the subsequent postprocessing of results to generate surge versus frequency-of-occurrence relationships.

3 Empirical Simulation Technique

The EST is a statistical model that simulates life-cycle sequences of cyclic but nondeterministic multiparameter systems such as storm events and their corresponding environmental impacts. A complete description of the EST with examples is given in Scheffner et al. 1999. The approach is based on a "bootstrap" resampling-with-replacement, interpolation, and subsequent smoothing technique in which random sampling of a finite length database is used to generate a larger database. The only assumption is that future events will be statistically similar in magnitude and frequency to past events. The EST begins with an analysis of historical storm events that have impacted a specific region. The selected database of events are then parameterized to define: (a) the descriptive characteristics of the event and (b) the impacts of the event. Parameters that define the storm are referred to as input vectors. Response vectors define storm-related impacts such as inundation and shoreline/dune erosion. For the South Carolina study, the response vector of interest is the maximum water-surface elevation (i.e., storm surge plus tide) at each location shown in Figure 5. These input and response vectors are then used as a basis for generating life-cycle simulations of storm event activity with the EST. Details of the approach follow.

Input vectors define certain descriptive characteristics of the storm event with respect to the specific location of interest. For tropical events, five vectors at each station are defined at the point when the eye of the hurricane is closest to the station of interest. These vectors are defined as:

a. Tidal phase during the event, with 1.0 corresponding to an M_2 constituent high-water slack, 0.0 for mean sea level (msl) at maximum ebb, -1.0 low water slack, and 0.0 msl at maximum flood.

b. Minimum distance from the eye of the storm to the location of interest in statute miles.

c. Central pressure deficit of the hurricane eye in mb.

d. Maximum winds in the hurricane, measured in knots.

e. Forward speed of the eye of the hurricane, measured in statute miles per hour.

Extratropical event input vectors are defined as:

a. A multiplier of the M_2 tidal constituent to indicate maximum elevations achieved during each of four phases of the lunar month. For example, spring tide, mean tide, neap tide, and mean tide.

b. Peak tidal elevation.

c. Surge elevation with no tidal contribution.

Response vectors describe any physical impact that can be attributed to the passage of the storm being parameterized by input vectors. For the coast of South Carolina study, the specified response vector is the maximum water-surface elevation; however, additional responses such as shoreline erosion or inundation can be specified. Each surge elevation was determined by simulating the specific storm event via the ADCIRC hydrodynamic model using the computational domain shown in Figure 2. Details of the use of the input/response vector space for the generation of life-cycle storm event simulations and the subsequent computations of frequency relationships are given in the following paragraphs.

Once a training set of events has been defined with each event/station represented by an appropriate input and response vector set, life-cycle simulations via the EST can be generated. The goal of the EST can be summarized as:

a. Given the following:

(1) The historical data ($v_i \varepsilon \Re^d v$; $i=1, ..., I$)

(2) The "training set" data ($v^*_j \varepsilon \Re^d v$; $j=1, ..., J$)

(3) The response vectors calculated from the training set ($r^*_j \varepsilon \Re^d r$; $j=1, ..., J$)

where $\Re^d v$ and $\Re^d r$ represent a d_v- and d_r-dimensional space of historical data.

b. Produce N simulations of a T-year sequence of events, each with their associated input vectors $v \varepsilon \Re^d v$ and response vectors $r \varepsilon \Re^d r$.

Two criteria are required of the T-year sequence of events. The first criterion is that the individual events must be similar in behavior and magnitude to historical events, i.e., the interrelationships among the input and response vectors must be realistic. The second criterion is that the frequency of storm events in the future will remain the same as the past. The following sections describe how these two criteria are preserved.

Storm Event Consistency

The first major assumption in the EST is that future events will be similar to past events. This criterion is maintained by ensuring that the input vectors for simulated events are similar to those of past events and have similar joint probabilities to those historical or historically-based events of the training set. For example, a hurricane with a large central pressure deficit and low maximum winds is not a realistic event—the two parameters are not independent although their precise dependency is unknown. The simulation of realistic events is accounted for in the nearest-neighbor interpolation, bootstrap, resampling technique developed by Borgman (Scheffner et al. 1999; Borgman et al. 1992).

The basic technique can be described in two dimensions as follows. Let $X_1, X_2, X_3, ..., X_n$ be n independent, identically distributed random vectors (storm events), each having two components $[X_i = \{\underline{x}_i(1), \underline{x}_i(2)\}; i=1,n]$. Each event X_i has a probability p_i as 1/n, therefore, a cumulative probability relationship can be developed in which each storm event is assigned a segment of the total probability of 0.0 to 1.0. If each event has an equal probability, then each event is assigned a segment s_j so that $s_j \rightarrow X_j$. Therefore each event occupies a fixed portion of the 0.0 to 1.0 probability space according to the total number of events in the training set. If each event has an equal probability, then each event is assigned a segment s_j so that $s_j \rightarrow X_j$ and has probabilities defined by:

$$\left(0 < s_1 \leq \frac{1}{n}\right)$$

$$\left(\frac{1}{n} < s_2 \leq \frac{2}{n}\right)$$

$$\left(\frac{2}{n} < s_3 \leq \frac{3}{n}\right)$$

$$\vdots$$

$$\left(\frac{n-1}{n} < s_n \leq 1\right)$$

A random number from 0 to 1 is selected to identify a storm event from the total storm population. The procedure is equivalent to drawing and replacing random samples from the full-storm event population.

The EST is not simply a resampling of historical events technique, but rather an approach intended to simulate the vector distribution contained in the training set database population. The EST approach is to select a sample storm based on a random number selection from 0 to 1 and then perform a random walk from the event X_i with x_1 and x_2 response vectors to the nearest neighbor vectors. The walk is based on independent uniform random numbers on (-1,1) and has the effect of simulating responses that are not identical to the historical events but are similar to events which have historically occurred.

Storm Event Frequency

The second criterion to be satisfied is that the total number of storm events selected per year must be statistically similar to the number of historical events that have occurred at the location of concern. Given the mean frequency of storm events for a particular region, a Poisson distribution is used to determine the average number of expected events in a given year. For example, the Poisson distribution can be written in the following form:

$$Pr(s;\lambda)=\frac{\lambda^s e^{-\lambda}}{s!} \tag{5}$$

The probability $Pr(s;\lambda)$ defines the probability of having s events per year where λ is the historically based number of events per year. In the South Carolina study, historical data (described in a subsequent section) were used to define λ as follows:

Tropical events: $\lambda = 0.2308$ (24 events/104 years)

Extratropical events: $\lambda = 0.5625$ (9 events/16 winter seasons)

Output from the EST program is N repetitions of T-years of simulated storm event responses. For the South Carolina study, N=100 repetitions of a T=200 year sequence of storm activity are used. It is from the responses of those simulations that frequency-of-occurrence relationships are computed. The computational procedure followed is based on the generation of a probability distribution function corresponding to each of the T-year sequences of simulated data. In the following section, the approach adopted for using these storms to develop frequency-of-occurrence relationships is given.

Recurrence Relationships

Estimates of frequency-of-occurrence begin with the calculation of a probability distribution function (pdf) for the response vector of interest. Let $X_1, X_2, X_3, \ldots, X_n$ be n independent, identically distributed, random response variables with a cumulative pdf given by

$$F_X(x) = Pr(X \leq x)$$

where $Pr(X \leq x)$ represents the probability that the random variable X is less than or equal to some value x, and $F_x(x)$ is the cumulative probability density function ranging from 0.0 to 1.0. The problem is to estimate the value of F_x without introducing some parametric relationship for probability. The following procedure is adopted because it makes use of the probability laws defined by the data and does not incorporate any prior assumptions concerning the probability relationship.

Assume a set of n observations of data. The n values of x are first ranked in order of increasing size. In the following analysis, the parentheses surrounding the subscript indicate that the data have been rank-ordered. The value $x_{(1)}$ is the smallest in the series and $x_{(n)}$ represents the largest value. Let r denote the rank of the value $x_{(r)}$ so that rank r=1 is the smallest and rank r=n is the largest.

An empirical estimate of $F_x(x_{(r)})$, denoted by $\hat{E}_x(x_{(r)})$, is given by Gumbel (1954) (see also Borgman and Scheffner (1991) and Scheffner and Borgman (1992)) as

$$\hat{F}_X\left(x_{(r)}\right) = \frac{r}{(n+1)} \qquad (6)$$

for $\{x_{(r)}, r = 1,2,3,\ldots,n\}$. This form of estimate allows for future values of x to be less than the smallest observation $x_{(1)}$ with a cumulative pdf of 1/(n+1), and to be larger than the largest values $x_{(n)}$ with cumulative pdf of n/(n+1).

An example set of 10 years of observed elevations, the rank ordered set of observations, the rank, and the cumulative pdf computed according to Equation 6 are shown in Table 5. As can be seen in the table, this form of the cumulative distribution function allows for values of x to be greater than the maximum (pdf > 0.91) or less than the minimum (pdf < 0.10) observed values in the historical database. A plot of the cumulative distribution function versus $x_{(r)}$ as computed by Equation 6 is shown in Figure 8. In the implementation of the EST, tail functions (Borgman and Scheffner 1991) are applied to define the pdf for events larger than the largest or

smaller than the smallest observed event so that there is no discontinuity in the pdf.

Table 5. Sample Distribution Function Calculation

Year	$X_{1,2,\ldots,n}$	$X_{(r)}$	Rank r	$\hat{F}_X(X_{(r)})$
1	3.2	10.5	10	0.91
2	3.5	8.6	9	0.82
3	8.0	8.0	8	0.73
4	1.0	7.5	7	0.64
5	10.5	5.9	6	0.55
6	5.9	4.1	5	0.45
7	8.6	3.5	4	0.36
8	4.1	3.2	3	0.27
9	2.3	2.3	2	0.18
10	7.5	1.0	1	0.10

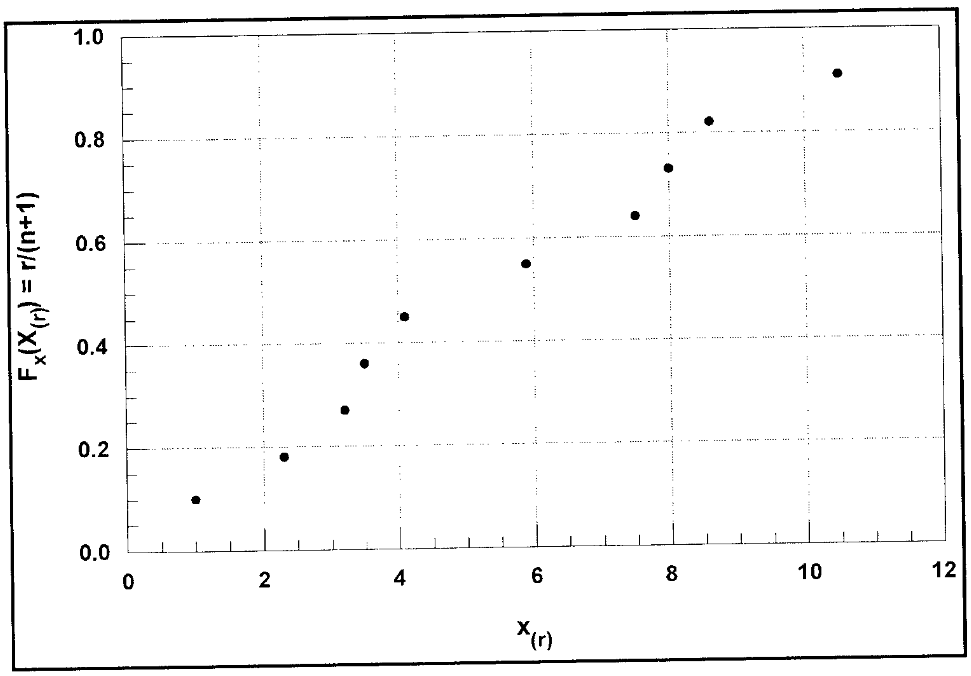

Figure 8. Example of cumulative probability distribution plot

The cumulative pdf as defined by Equation 6 and shown in Figure 8 is applied to develop stage-frequency relationships as follows. Consider that the cumulative probability for an n-year return period storm can be written as

$$F(n) = 1 - \frac{1}{n} \qquad (7)$$

where F(n) is the simulated cumulative pdf for an event with a return period of n years. Frequency-of-occurrence relationships are obtained by linearly interpolating a stage from Equation 6 corresponding to the pdf associated with the return period calculated by Equation 7.

Equations 6 and 7 are applied to each of the N-repetitions of T-years of storm events simulated via the EST. Therefore, there are N frequency-of-occurrence relationships generated. Then, for each return period year, a standard deviation, defined as:

$$\sigma = \sqrt{\left[(1/N) \sum_{n=1}^{n=N} \left(x_n - \bar{x} \right)^2 \right]}$$

(where $\bar{x}$ is the mean value), is computed to define an error band of ±1 standard deviation corresponding to each mean value curve.

Combined Tropical/Extratropical Frequency Relationships

The calculation of frequency-of-occurrence relationships for combined tropical and extratropical events occurring within the same year begins with the assumption that tropical and extratropical events are independent. This relationship is made explicit by stating that the probability of both events occurring in a given year is equal to the product of the probability of each separate event occurring in the same year. For example,

$$F_{comb}\left(x_{(n)}\right) = F_1\left(x_{(n)}\right) F_2\left(x_{(n)}\right) \qquad (8)$$

defines the probability of two independent n-year events occurring the same year.

Using the definition of Equation 7 for the cumulative pdf for an n-year event, Equation 8 can be written in terms of the return periods associated with either event as:

$$F_{comb} = F_1 F_2 = \left(1 - \frac{1}{R_1}\right)\left(1 - \frac{1}{R_2}\right) = 1 - \frac{1}{R_{comb}}$$

where $F_{comb}(x)$, $F_1(x)$, and $F_2(x)$ are the combined, tropical and extratropical event cdf's and $R_{comb}(x)$, $R_1(x)$, and $R_2(x)$ the respective return period in years.

Then the combined event return period $R_{comb}(x)$ for an n-year event can be written as

$$R_{comb}(x) = \frac{1}{\frac{1}{R_1(x)} + \frac{1}{R_2(x)} - \frac{1}{R_1(x) R_2(x)}} \qquad (9)$$

where $R_{comb}(x)$ represents the combined return period associated with the occurrence in the same year of both a tropical and extratropical event with return periods of R_1 and R_2. Because the product of $R_1(x)R_2(x)$ is large with respect to $R_1(x)$or $R_2(x)$, the relationship of Equation 9 can be approximated as

$$R_{comb}(x) = \frac{1}{\frac{1}{R_1(x)} + \frac{1}{R_2(x)}}$$

To implement the previously presented concepts, a "training set" of historic events for the study area has to be defined. The following section documents the construction of the training set for the coast of South Carolina study.

Training Set Selection

The advantage of the EST over other frequency computation methods such as the Joint Probability Method (JPM) is that the input/response vector space describes events that can or have occurred at the location of interest. This is assured by creating the vector space from a set of storm

events that have impacted or could impact the area of interest. The storms used to populate the input/response vector space are referred to as the training set of events. Each event of the training set must be a realistic event for the area, either a historic event or a hypothetical event based on a historic event with, for example, a slightly altered path or radius to maximum wind, i.e., a hypothetical event that could occur. Site specificity is then assured because the joint probabilities among the various input/ response vectors reflects the joint probabilities inherent in parameters descriptive of actual events (or some slight variation of) which are site specific. The following sections describe the construction of the training sets of storms.

Tropical events

A tropical storm database (Scheffner et al. 1994) was generated during the DRP through simulation of 134 historically-based storm events along the East Coast, Gulf of Mexico, and Caribbean Sea. Based on the HURDAT database. For 486 discrete locations along the U.S. coast, peak storm surge values corresponding to storm events which produced a surge of at least 0.305 m (1.0 ft) were archived and indexed according to event, location, and surge magnitude. This indexed database was used to define an initial training set for the present study.

Ideally, historical events represent the full range of possible event intensities. If this occurs, the historical events can be used directly to develop the full training set of storms. For extratropical events, this is generally the case because extratropical events occur often, cover extremely large areas, and persist for long periods of time (i.e., days). However, with tropical events this is often not the case. At many locations, the worst case tropical event scenario may not yet have occurred but may represent a historic event with a slightly shifted path or larger/smaller radius to maximum wind. Because the accuracy of the EST is dependent upon a full training set, some augmentation of the historic events is often necessary. Although 24 events have historically impacted the study area, storm augmentation was found to be necessary for the South Carolina study because station locations of interest span over 150 miles. For example, Hurricane Hugo made a near-perpendicular landfall near Charleston on 21 September 1989 as shown by the plot of Hurricane Hugo's track on Figure 9. Although the event generated severe surges for areas north and east of Charleston, areas south and west of landfall were not severely impacted.

Four additional storm events were added to supplement the initial training set. This allowed all stations within the study to experience a maximum intensity event, and it thereby filled the vector space with events ranging from nominal to intense. These events were developed as perturbations of Hurricane Hugo, one of the most intense events of record. Because locations south and west of landfall were not severely impacted, four hypothetical events created by assuming the historical path of Hurricane Hugo, were shifted 1 and 2 deg west of landfall and 1 and 2 deg east of landfall. These four combinations, along with the historical event produced maximum

surges throughout the study area. The final training set consisted of 28 events; 24 historical, and four hypothetical representing perturbations of Hurricane Hugo. The final training set is shown in Table 6.

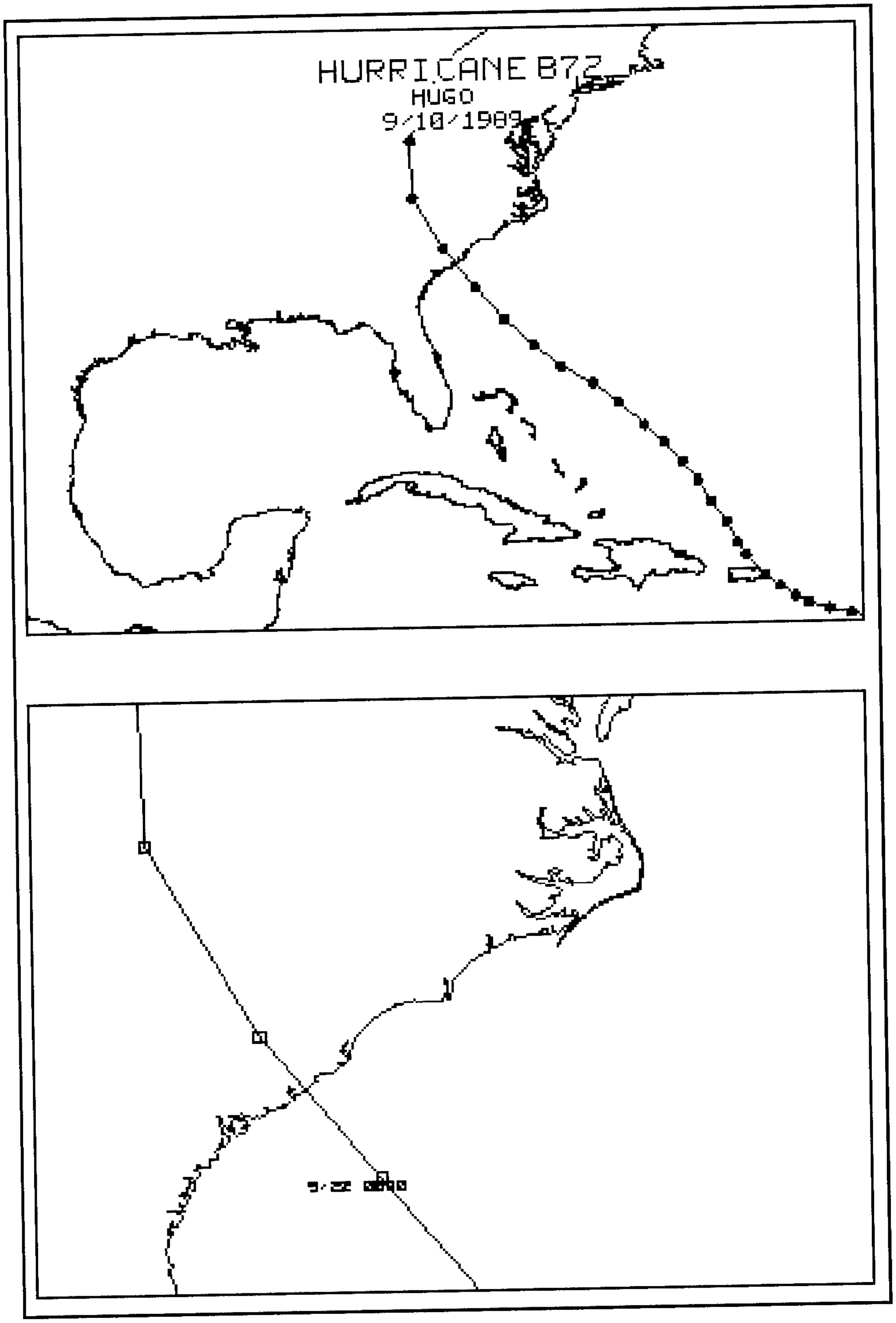

Figure 9. Track of Hurricane Hugo

Table 6. Tropical Events Impacting Study Area

HURDAT[1]	Storm #	Given Name	Date (mo/dy/yr)
1	194	Not Named	10/09/1910
2	196	Not Named	08/23/1911
3	217	Not Named	07/11/1916
4	292	Not Named	09/06/1928
5	296	Not Named	09/22/1929
6	299	Not Named	08/31/1930
7	353	Not Named	08/29/1935
8	398	Not Named	08/05/1940
9	440	Not Named	10/12/1944
10	449	Not Named	09/12/1945
11	463	Not Named	09/20/1947
12	465	Not Named	10/09/1947
13	521	Not Named	08/28/1953
14	526	Florence	09/23/1953
15	541	Hazel	10/05/1954
16	562	Flossy	09/21/1956
17	589	Gracie	09/20/1959
18	597	Donna	08/29/1960
19	643	Alma	06/04/1966
20	669	Gladys	10/13/1968
21	777	David	08/25/1979
22	797	Dennis	08/07/1981
23	839	Kate	11/15/1985
24	872	Hugo	09/10/1989
25	872A	Hugo-A	—
26	872B	Hugo-B	—
27	872C	Hugo-C	—
28	872D	Hugo-D	—

[1] The HURDAT storm number designation refers to the storm identification number of the events in the National Hurricane Center database of historic tropical events, and the time signifies the first time of storm on record.

Extratropical events

In an approach similar to that of the tropical event database described previously, an extratropical storm event database was generated within the DRP. This database was constructed by driving the ADCIRC model with wind fields extracted from the U.S. Navy Fleet Numerical Meteorology and Oceanography Center's database of winds for the 16-year winter storm period (defined as September through March) of 1977 through 1993 (77-78, 78-79, etc.). These wind-field data are provided at 6-hr intervals on a 2.5° latitude and longitude grid. The extratropical storm database consists

of a 7-month surface elevation and current hydrograph at each of the 486 stations described. These data contain severe events occurring during the 16-year sequence of winter months; however, unlike tropical events that are clearly distinguishable, identification of individual extratropical events within the records requires additional analysis.

Time series surface elevation plots corresponding to an archived station near the center of the study area were analyzed. Each time series represented surge with no tide. A typical 7-month time series for DRP sta 416 located offshore of the entrance to Charleston for the extratropical storm year 1982-1983 is shown in Figure 10. In this figure, day 1 refers to 1 September 1982 and day 212 refers to 31 March 1983. As shown in the figure, a storm event is shown just following day 180, corresponding to approximately 1 February 1983. Similar plots for each of the 16-year seasons were plotted and 9 events were selected to populate the extratropical storm event

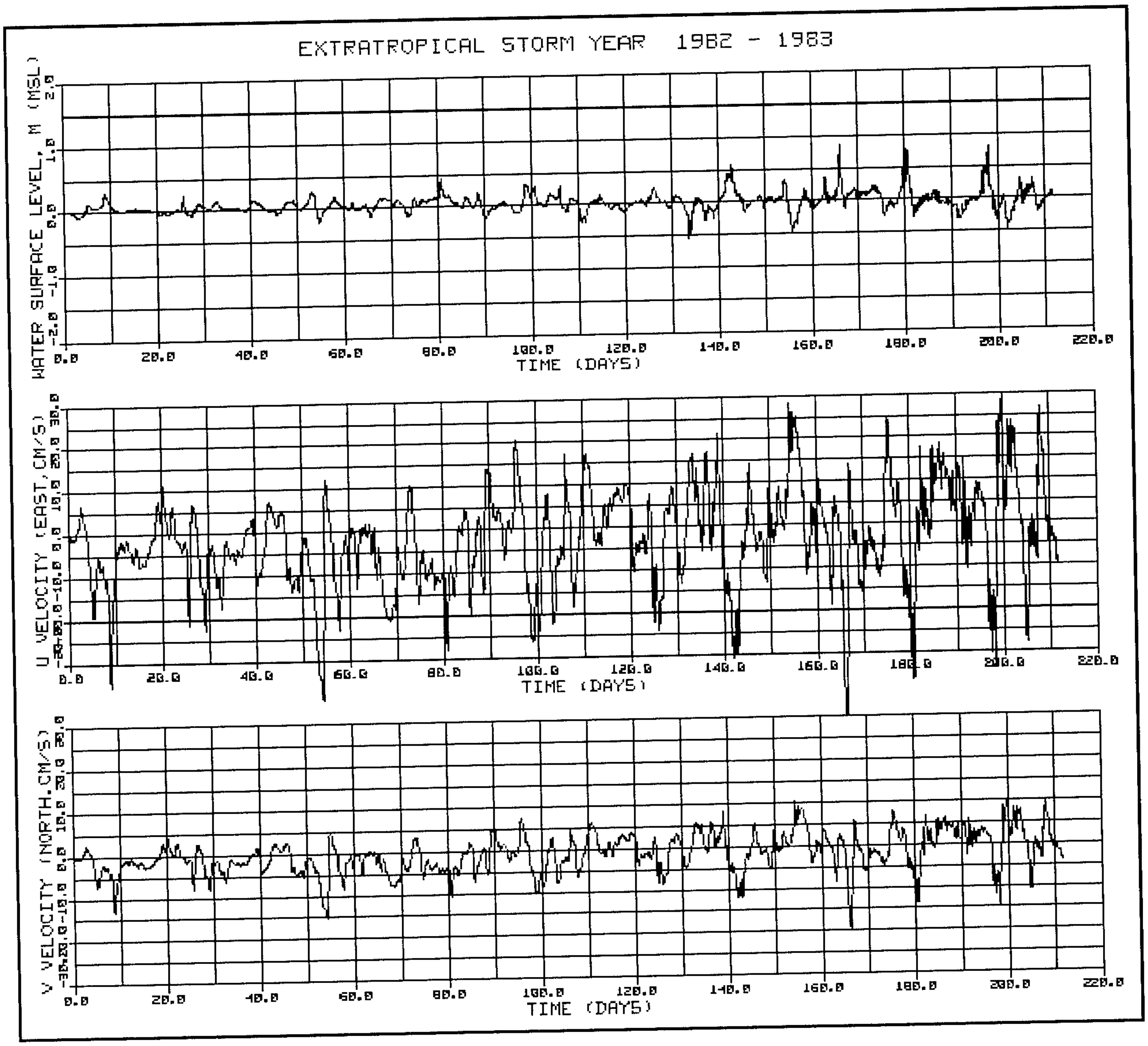

Figure 10. Extratropical storm year 1981-1983 for DRP sta 416

database for the EST. The approximate starting time for each of the nine events is shown in Table 7.

Table 7. Extratropical Events Impacting Study Area

Storm Number	Starting Date
1	13 February 1979
2	1 September 1979
3	8 February 1983
4	24 February 1983
5	13 March 1983
6	5 September 1984
7	24 October 1985
8	1 January 1987
9	13 February 1987

The storm events of Tables 6 and 7 represent the range of intensities of tropical and extratropical events that have or could impact the study area. These events have historically occurred or have a reasonable potential for occurring based on past storm activity. In the following section, the approach for using these storms to develop frequency-of-occurrence relationships is given.

4 Frequency Analysis

The overall frequency analysis procedure begins by defining a historical storm-based training set of both tropical and extratropical events that impacted the coast of South Carolina. These events are shown in Tables 6 and 7. Each of these defined storms are simulated over the computational grid via the ADCIRC and PBL models with maximum surge elevations archived for each station location shown in Figure 5. Additionally, a 31-day ADCIRC simulation was used to perform a 28-day harmonic analysis to generate an eight-constituent tidal constituent database for each of the 38 stations of Figure 5. Each of the 28 tropical and nine extratropical events of the training set are parameterized to develop a database of input vectors for each event corresponding to each station location. Model-generated surge and tidal elevations are then used to generate response vectors for each station corresponding to each event of the tropical and extratropical training set. Details of the computation of the response vectors are given.

Each storm of the training set was simulated without tide to produce one set of input-response vector combination for each location for each storm. This single set was then used to generate four vectors representing four phases of the tide. For rapidly moving tropical events, the phases were constructed by linearly adding/subtracting the local M_2 constituent amplitude to the local maximum surge to create a storm occurring at high tide, mean tide, low tide, and mean tide. For slow moving extratropical events which usually span a single tidal cycle, the four phases are constructed by assuming the storm has an equal probability of occurring at spring tide, between spring and neap, at neap tide, and between neap and spring. Based on an analysis of the eight-constituent tide at Savannah and Charleston, maximum elevation criteria for spring tide, mean tide, and neap tide was a multiplier of the local M_2 amplitude of 1.165, 1.030, and 0.895. This procedure produced a tropical training set of 112 (4×28) tropical and 36 (4×9) extratropical input/response vector sets. These vector sets were then input to the EST to generate 100 separate simulations of 200 years of tropical and 200 years of extratropical storm activity for each of the 38 study stations. Postprocessing of the output yields a mean value frequency-of-occurrence and a ±1 standard deviation error estimate for each station for both tropical and extratropical events. Finally, these two frequency

relationships are used to compute combined event frequency relationships according to the assumption previously described.

In the EST analysis, a 200-year life-cycle of storm activity was simulated to provide frequency estimates through the 200-year return period event. A 500-year return period estimate for maximum water level was requested so that a 500-year event could be provided as input to the Santee River Flood Control Project. A 500-year estimate cannot reliably be made based on only 100 years of observation. However, 500-year estimates were made based on extrapolation of the 199- and 200-year estimate from the postprocessed EST results. This 500-year estimate should be used with caution. An example frequency summary table for the Charleston Inner Harbor gage is given in the following table in which the tropical storm surge, extratropical storm surge, and combined event surge are given for specified return periods. For example, the total surge (tide plus storm surge) for a 100-year return period tropical event is 4.04 m. All frequency tables corresponding to stations 1-38 of Figure 5 are given in Appendix A. Note in Table 8 and all tables of Appendix A that mimimum values of surge elevation are set to a constant value with no standard deviation. This constant value reflects the fact that the computed extratropical event was less than the extreme tide of the spring solstice, which occurs in mid June. Therefore, a tidal simulation of 15 June through 15 July was simulated, and an approximate equivalent multiplier for the local M_2 computed to be 1.50. Therefore, if the EST-generated surge is less than this value, the surge elevation is set equal to 1.5 times the M_2 amplitude.

Table 8. Frequency Summary for Charleston Inner Harbor Gage Location

Return Period, Yrs	Tropical, SD Total Surge, m	Extratropical, SD Total Surge, m	Combined, SD Total Surge, m
2.00	1.18 (0.00)	1.18 (0.00)	1.18 (0.00)
5.00	1.18 (0.00)	1.59 (0.03)	1.65 (0.15)
10.00	1.18 (0.00)	1.70 (0.05)	2.04 (0.38)
15.00	1.71 (0.34)	1.84 (0.16)	2.41 (0.50)
20.00	2.07 (0.40)	2.03 (0.24)	2.63 (0.63)
25.00	2.38 (0.40)	2.18 (0.25)	2.79 (0.64)
50.00	3.27 (0.55)	2.58 (0.22)	3.45 (0.77)
100.00	4.04 (0.66)	2.83 (0.20)	4.22 (0.86)
150.00	4.50 (0.84)	3.00 (0.24)	4.65 (1.09)
200.00	4.74 (0.98)	3.09 (0.29)	4.89 (1.28)
500.00	5.82 (1.80)	3.67 (0.29)	6.33 (2.10)

5 Santee River Flood Control Project Input Hydrographs

The second and final phase of this project is the generation of frequency-indexed surface elevation hydrographs to serve as boundary conditions for the RMA numerical modeling effort for the Santee River Flood Control Project. Hydrographs were requested to represent return periods of 2, 25, 50, 100, and 500 years. Locations for the 33 boundary nodes of the RMA grid are shown in Figure 11 along with the ADCIRC surge study nodes for Savannah River (No. 1), Charleston Inner Harbor (No. 21), Charleston Harbor (No. 23), South Santee (No. 28) and North Santee (No. 29).

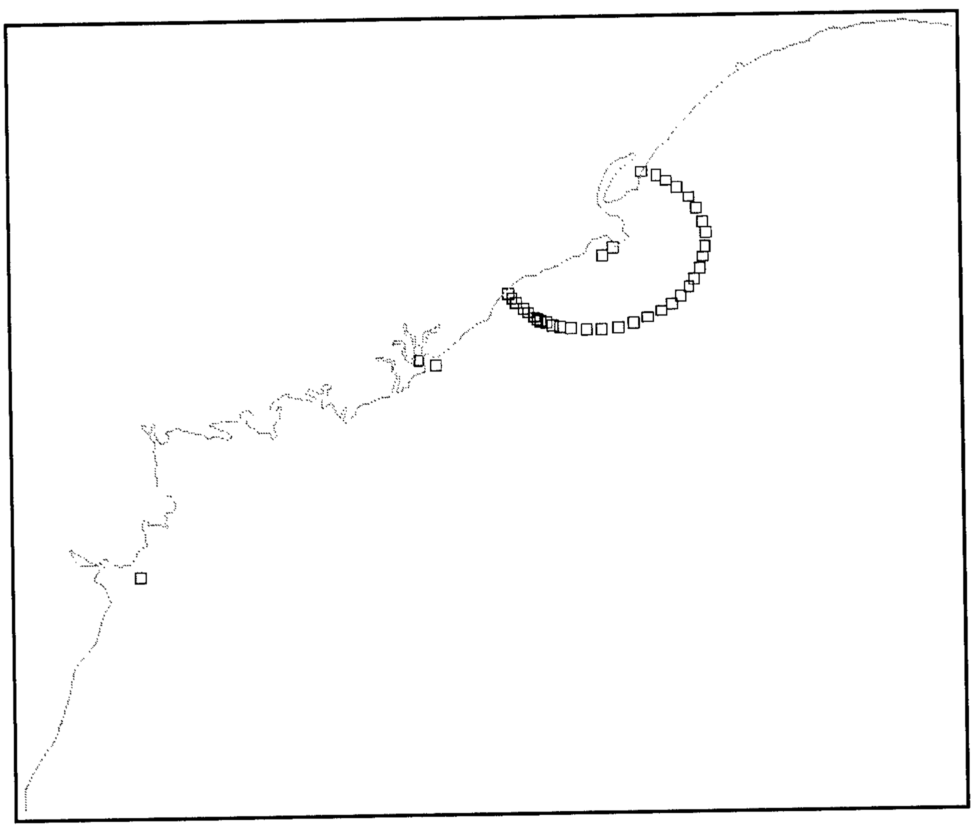

Figure 11. Boundary node locations for RMA model

Results shown in Appendix A were used to define peak surge elevations at ADCIRC Stations 28 and 29 corresponding to the requested return periods. Frequency-indexed input hydrographs were constructed by first assuming the storm to occur at high tide and then linearly scaling the amplitude of the hydrograph of a selected historical storm so that the total water-surface elevation approximates that of the desired frequency-indexed elevation given in the tables. Data used for the generation of the RMA input hydrographs is given in Table 9. For example, the 100-year peak surface elevation for sta 28 was shown to be 4.70 m in the EST analysis. A 100-year storm was constructed by multiplying the 2.20 m surge of historical storm 194 by 1.18 and adding an M_2 tide with a peak value of 0.7 m that coincides with the peak of the scaled historical storm.

Table 9. Frequency-Indexed Surge Hydrograph Construction (sta 28)

Return Period, yr	Peak Surge, m	Historical Surge, m x multiplier	Tide (M_2 - m)	Total Water Level Surge x mult + tide, m
2	1.05	21 June 2000	—	1.05
25	2.05	217-1.25×1.08	0.7	2.05
50	2.70	353-1.50×1.33	0.7	2.70
100	3.30	194-2.20×1.18	0.7	3.30
500	4.70	872-2.35×1.70	0.7	4.70

6 Summary and Conclusions

This report describes details of a two-phase investigation of storm-generated water levels along the open coast and up the major tributaries of South Carolina. In the first phase, tropical and extratropical storm events that have historically impacted the coast of South Carolina were simulated using the long-wave hydrodynamic model ADCIRC. The resulting storm surge elevations with corresponding tides were analyzed to develop combined event stage frequency-of-occurrence relationships at 38 selected locations within the study area. The second phase of the study was to generate frequency-indexed storm surge hydrographs for a separate modeling effort involving the Santee River Flood Control Project. This study was performed by ERDC, CHL, for the Charleston District.

Conclusions of the study are that the EST statistical approach to frequency analysis is conceptually superior to alternate approaches such as the Joint Probability Method (JPM) or rank ordering of historical event observations. Although the JPM has been widely used in the past for storm surge analyses, the approach is based on the assumption that storms can be parameterized according to defined relationships, and it assumes that storm parameters are independent (or partially dependent according to some parameterized relationship). This assumption is not entirely valid. For example, pressure deficit, maximum wind, and radius to maximum wind are not independent parameters. Therefore, a joint pdf based on assumed independence can lead to error in the computed joint pdf. For the historical ranking approach, surge magnitudes are dependent on observations; therefore, the largest frequency-indexed event is limited by the storm of record.

The EST was developed primarily to address the inherent disadvantages of alternate frequency analyses. The EST utilizes observed and/or computed parameters associated with site specific historical events as a basis for developing a methodology for generating multiple life cycle simulations of storm activity and the effects associated with each simulated event. Contrary to the JPM, the technique does not rely on assumed parametric relationships but uses the joint probability relationships inherent in the local database. Therefore, in this approach, probabilities are site specific, do not depend on fixed parametric relationships, and do not assume parameter independence. Thus, the EST is "distribution free" and nonparametric.

Frequency relationships developed in this study are realistic in magnitude and are consistent with published frequency curves. For example, frequency-indexed surge elevations reported by NOAA (Myers 1975) for Sullivans Island are approximately 0.305 m (1.0 ft) greater than values computed for the Charleston Harbor gage (sta 23) located adjacent to Sullivans Island. Additionally, NOAA reported surges at the Georgia-South Carolina border are comparable to study results generated for the Savannah River gage (sta 1). If ADCIRC/EST-generated results at these two locations are considered acceptable, a major benefit of this study is the generation of 36 additional frequency curves for locations at which reliable frequency relationships are not available. Finally, results have been used to generate frequency-indexed storm event boundary conditions for the Santee River Flood Control Project. Use of this data should provide for the risk-based design criteria currently being required for Corps projects.

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Appendix A
Stage Frequency Relationships

SOUTH CAROLINA STATION 1 Savannah River

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.42 (0.00)	1.42 (0.00)	1.42 (0.00)
5.00	1.42 (0.00)	1.67 (0.04)	1.80 (0.16)
10.00	1.42 (0.00)	1.85 (0.05)	2.04 (0.50)
15.00	1.97 (0.49)	1.93 (0.05)	2.24 (0.53)
20.00	2.42 (0.50)	1.98 (0.05)	2.45 (0.55)
25.00	2.78 (0.49)	2.02 (0.06)	2.79 (0.55)
50.00	3.64 (0.52)	2.13 (0.07)	3.65 (0.59)
100.00	4.41 (0.75)	2.24 (0.11)	4.41 (0.86)
150.00	4.99 (0.96)	2.32 (0.12)	4.99 (1.08)
200.00	5.28 (1.11)	2.35 (0.14)	5.29 (1.26)
500.00	6.66 (1.97)	2.43 (0.14)	6.68 (2.11)

SOUTH CAROLINA STATION 2 Calibogue Sound

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.43 (0.00)	1.43 (0.00)	1.43 (0.00)
5.00	1.43 (0.00)	1.67 (0.04)	1.80 (0.17)
10.00	1.43 (0.00)	1.84 (0.04)	2.02 (0.50)
15.00	2.07 (0.50)	1.91 (0.04)	2.24 (0.54)
20.00	2.53 (0.45)	1.95 (0.05)	2.59 (0.50)
25.00	2.85 (0.47)	1.98 (0.05)	2.89 (0.52)
50.00	3.67 (0.50)	2.08 (0.06)	3.71 (0.56)
100.00	4.47 (0.73)	2.18 (0.10)	4.52 (0.83)
150.00	4.96 (0.87)	2.26 (0.11)	5.01 (0.98)
200.00	5.20 (0.99)	2.30 (0.13)	5.26 (1.12)
500.00	6.36 (1.71)	2.60 (0.13)	6.54 (1.84)

SOUTH CAROLINA STATION 3 Broad River

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.62 (0.00)	1.62 (0.00)	1.62 (0.00)
5.00	1.62 (0.00)	2.01 (0.05)	2.12 (0.29)
10.00	2.03 (0.61)	2.13 (0.02)	2.35 (0.63)
15.00	2.91 (0.55)	2.17 (0.03)	2.92 (0.58)
20.00	3.43 (0.49)	2.20 (0.04)	3.43 (0.53)
25.00	3.79 (0.44)	2.23 (0.05)	3.79 (0.48)
50.00	4.61 (0.49)	2.31 (0.05)	4.61 (0.54)
100.00	5.42 (0.80)	2.37 (0.06)	5.43 (0.86)
150.00	5.91 (0.92)	2.41 (0.06)	5.92 (0.99)
200.00	6.16 (1.04)	2.43 (0.07)	6.16 (1.11)
500.00	7.33 (1.76)	2.44 (0.07)	7.34 (1.83)

SOUTH CAROLINA STATION 4 Whale Branch

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	, EXTROPIC (SD)	, COMBINED (SD)
2.00	1.53 (0.00)	1.53 (0.00)	1.53 (0.00)
5.00	1.53 (0.00)	2.06 (0.05)	2.21 (0.33)
10.00	2.17 (0.65)	2.21 (0.05)	2.69 (0.70)
15.00	3.10 (0.54)	2.31 (0.08)	3.21 (0.62)
20.00	3.65 (0.49)	2.39 (0.10)	3.69 (0.59)
25.00	4.01 (0.47)	2.46 (0.12)	4.04 (0.58)
50.00	4.81 (0.53)	2.69 (0.15)	4.84 (0.68)
100.00	5.64 (0.81)	2.91 (0.18)	5.69 (0.99)
150.00	6.16 (0.92)	3.03 (0.20)	6.21 (1.12)
200.00	6.42 (1.03)	3.10 (0.23)	6.47 (1.25)
500.00	7.65 (1.65)	3.41 (0.23)	7.82 (1.88)

SOUTH CAROLINA STATION 5 Beaufort River

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	, EXTROPIC (SD)	, COMBINED (SD)
2.00	1.53 (0.00)	1.53 (0.00)	1.53 (0.00)
5.00	1.53 (0.00)	1.83 (0.05)	1.92 (0.23)
10.00	1.60 (0.47)	1.94 (0.02)	2.09 (0.49)
15.00	2.31 (0.46)	1.98 (0.03)	2.33 (0.49)
20.00	2.74 (0.44)	2.01 (0.04)	2.74 (0.48)
25.00	3.06 (0.41)	2.04 (0.04)	3.07 (0.44)
50.00	3.84 (0.44)	2.11 (0.05)	3.84 (0.48)
100.00	4.58 (0.71)	2.18 (0.05)	4.59 (0.76)
150.00	5.05 (0.81)	2.21 (0.06)	5.05 (0.87)
200.00	5.28 (0.92)	2.22 (0.07)	5.28 (0.98)
500.00	6.34 (1.54)	2.30 (0.07)	6.36 (1.61)

SOUTH CAROLINA STATION 6 Port Royal Sound

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	, EXTROPIC (SD)	, COMBINED (SD)
2.00	1.41 (0.00)	1.41 (0.00)	1.41 (0.00)
5.00	1.41 (0.00)	1.65 (0.04)	1.75 (0.11)
10.00	1.41 (0.00)	1.78 (0.03)	1.92 (0.43)
15.00	1.95 (0.40)	1.83 (0.03)	2.09 (0.43)
20.00	2.35 (0.40)	1.87 (0.03)	2.36 (0.43)
25.00	2.64 (0.39)	1.89 (0.03)	2.64 (0.42)
50.00	3.37 (0.41)	1.96 (0.05)	3.38 (0.46)
100.00	4.07 (0.68)	2.05 (0.08)	4.07 (0.76)
150.00	4.52 (0.78)	2.10 (0.09)	4.53 (0.87)
200.00	4.75 (0.89)	2.12 (0.09)	4.75 (0.98)
500.00	5.79 (1.50)	2.13 (0.09)	5.81 (1.60)

SOUTH CAROLINA STATION 7 Coosaw River

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.45 (0.00)	1.45 (0.00)	1.45 (0.00)
5.00	1.45 (0.00)	1.94 (0.03)	2.06 (0.30)
10.00	2.00 (0.54)	2.06 (0.06)	2.63 (0.60)
15.00	2.82 (0.46)	2.18 (0.10)	3.07 (0.56)
20.00	3.30 (0.43)	2.29 (0.15)	3.38 (0.58)
25.00	3.59 (0.40)	2.40 (0.19)	3.64 (0.59)
50.00	4.31 (0.44)	2.74 (0.22)	4.36 (0.66)
100.00	5.09 (0.78)	3.00 (0.23)	5.15 (1.00)
150.00	5.55 (0.87)	3.16 (0.23)	5.60 (1.10)
200.00	5.78 (0.97)	3.24 (0.25)	5.84 (1.22)
500.00	6.87 (1.54)	3.53 (0.25)	7.07 (1.79)

SOUTH CAROLINA STATION 8 Trenchards Inlet

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.37 (0.00)	1.37 (0.00)	1.37 (0.00)
5.00	1.37 (0.00)	1.61 (0.04)	1.70 (0.20)
10.00	1.37 (0.00)	1.73 (0.03)	1.85 (0.42)
15.00	1.93 (0.40)	1.77 (0.03)	2.03 (0.42)
20.00	2.29 (0.39)	1.80 (0.03)	2.30 (0.42)
25.00	2.58 (0.35)	1.82 (0.03)	2.59 (0.39)
50.00	3.26 (0.39)	1.89 (0.05)	3.27 (0.44)
100.00	3.94 (0.62)	1.97 (0.07)	3.94 (0.68)
150.00	4.35 (0.71)	2.02 (0.08)	4.35 (0.78)
200.00	4.56 (0.82)	2.03 (0.08)	4.56 (0.90)
500.00	5.55 (1.43)	2.05 (0.08)	5.57 (1.51)

SOUTH CAROLINA STATION 9 Combahee River

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.42 (0.00)	1.42 (0.00)	1.42 (0.00)
5.00	1.42 (0.00)	1.96 (0.04)	2.09 (0.32)
10.00	2.08 (0.55)	2.09 (0.06)	2.74 (0.61)
15.00	2.91 (0.45)	2.21 (0.13)	3.19 (0.58)
20.00	3.34 (0.41)	2.36 (0.18)	3.49 (0.59)
25.00	3.64 (0.39)	2.49 (0.22)	3.71 (0.61)
50.00	4.34 (0.44)	2.91 (0.24)	4.40 (0.69)
100.00	5.12 (0.79)	3.24 (0.24)	5.19 (1.04)
150.00	5.58 (0.88)	3.40 (0.24)	5.64 (1.12)
200.00	5.82 (0.98)	3.49 (0.26)	5.88 (1.25)
500.00	6.94 (1.57)	3.80 (0.27)	7.15 (1.84)

SOUTH CAROLINA STATION 10 Ashepoo River

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	, EXTROPIC (SD)	, COMBINED (SD)
2.00	1.45 (0.00)	1.45 (0.00)	1.45 (0.00)
5.00	1.45 (0.00)	1.91 (0.04)	2.08 (0.34)
10.00	2.23 (0.61)	2.06 (0.08)	2.87 (0.69)
15.00	3.13 (0.47)	2.22 (0.15)	3.34 (0.62)
20.00	3.60 (0.44)	2.40 (0.22)	3.68 (0.67)
25.00	3.87 (0.43)	2.56 (0.24)	3.92 (0.67)
50.00	4.63 (0.50)	2.97 (0.22)	4.67 (0.72)
100.00	5.36 (0.69)	3.22 (0.22)	5.43 (0.91)
150.00	5.86 (0.79)	3.40 (0.26)	5.92 (1.05)
200.00	6.11 (0.89)	3.49 (0.30)	6.17 (1.20)
500.00	7.33 (1.45)	3.76 (0.31)	7.54 (1.76)

SOUTH CAROLINA STATION 11 Fripp Inlet

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	, EXTROPIC (SD)	, COMBINED (SD)
2.00	1.30 (0.00)	1.30 (0.00)	1.30 (0.00)
5.00	1.30 (0.00)	1.62 (0.04)	1.72 (0.21)
10.00	1.30 (0.00)	1.75 (0.03)	1.89 (0.40)
15.00	1.84 (0.35)	1.81 (0.04)	2.04 (0.38)
20.00	2.17 (0.34)	1.84 (0.04)	2.20 (0.38)
25.00	2.42 (0.35)	1.87 (0.05)	2.43 (0.40)
50.00	3.18 (0.43)	1.96 (0.06)	3.18 (0.49)
100.00	3.82 (0.53)	2.04 (0.09)	3.83 (0.62)
150.00	4.18 (0.62)	2.10 (0.11)	4.19 (0.74)
200.00	4.37 (0.73)	2.12 (0.12)	4.37 (0.85)
500.00	5.20 (1.34)	2.15 (0.13)	5.22 (1.47)

SOUTH CAROLINA STATION 12 St. Helena Sound

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	, EXTROPIC (SD)	, COMBINED (SD)
2.00	1.36 (0.00)	1.36 (0.00)	1.36 (0.00)
5.00	1.36 (0.00)	1.81 (0.04)	1.92 (0.26)
10.00	1.64 (0.48)	1.94 (0.05)	2.34 (0.53)
15.00	2.34 (0.43)	2.05 (0.10)	2.68 (0.53)
20.00	2.76 (0.38)	2.16 (0.14)	2.95 (0.52)
25.00	3.05 (0.39)	2.26 (0.16)	3.14 (0.55)
50.00	3.77 (0.43)	2.56 (0.18)	3.83 (0.61)
100.00	4.47 (0.71)	2.81 (0.18)	4.55 (0.89)
150.00	4.92 (0.84)	2.94 (0.19)	4.99 (1.03)
200.00	5.15 (0.95)	3.00 (0.20)	5.21 (1.15)
500.00	6.20 (1.56)	3.29 (0.21)	6.42 (1.77)

SOUTH CAROLINA STATION 13 Upper North Edisto

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.23 (0.00)	1.23 (0.00)	1.23 (0.00)
5.00	1.23 (0.00)	1.85 (0.02)	1.99 (0.30)
10.00	2.05 (0.58)	1.98 (0.06)	2.80 (0.64)
15.00	2.96 (0.52)	2.14 (0.19)	3.30 (0.72)
20.00	3.47 (0.44)	2.36 (0.29)	3.61 (0.72)
25.00	3.74 (0.39)	2.56 (0.29)	3.85 (0.68)
50.00	4.45 (0.43)	3.03 (0.26)	4.54 (0.69)
100.00	5.17 (0.72)	3.32 (0.23)	5.29 (0.96)
150.00	5.60 (0.79)	3.52 (0.30)	5.70 (1.08)
200.00	5.81 (0.87)	3.63 (0.35)	5.93 (1.22)
500.00	6.81 (1.40)	4.23 (0.36)	7.21 (1.75)

SOUTH CAROLINA STATION 14 South Edisto

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.33 (0.00)	1.33 (0.00)	1.33 (0.00)
5.00	1.33 (0.00)	1.71 (0.03)	1.80 (0.23)
10.00	1.51 (0.44)	1.82 (0.06)	2.20 (0.49)
15.00	2.15 (0.37)	1.93 (0.10)	2.53 (0.47)
20.00	2.55 (0.35)	2.04 (0.15)	2.77 (0.50)
25.00	2.81 (0.36)	2.14 (0.17)	2.95 (0.53)
50.00	3.51 (0.42)	2.45 (0.19)	3.58 (0.61)
100.00	4.23 (0.65)	2.71 (0.19)	4.30 (0.84)
150.00	4.60 (0.78)	2.84 (0.19)	4.66 (0.97)
200.00	4.80 (0.89)	2.91 (0.21)	4.86 (1.10)
500.00	5.70 (1.54)	3.21 (0.21)	5.91 (1.75)

SOUTH CAROLINA STATION 15 North Edisto

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.26 (0.00)	1.26 (0.00)	1.26 (0.00)
5.00	1.26 (0.00)	1.61 (0.03)	1.67 (0.21)
10.00	1.35 (0.39)	1.71 (0.06)	2.10 (0.46)
15.00	1.95 (0.34)	1.84 (0.14)	2.42 (0.48)
20.00	2.28 (0.33)	1.98 (0.20)	2.62 (0.53)
25.00	2.53 (0.30)	2.12 (0.21)	2.78 (0.51)
50.00	3.21 (0.42)	2.48 (0.19)	3.30 (0.61)
100.00	3.84 (0.62)	2.69 (0.18)	3.93 (0.80)
150.00	4.23 (0.73)	2.84 (0.22)	4.30 (0.94)
200.00	4.42 (0.83)	2.92 (0.25)	4.50 (1.09)
500.00	5.36 (1.44)	3.22 (0.26)	5.62 (1.70)

SOUTH CAROLINA STATION 16 Bohicket Creek

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	, EXTROPIC (SD)	, COMBINED (SD)
2.00	1.27 (0.00)	1.27 (0.00)	1.27 (0.00)
5.00	1.27 (0.00)	1.60 (0.03)	1.68 (0.21)
10.00	1.43 (0.42)	1.71 (0.06)	2.17 (0.48)
15.00	2.04 (0.36)	1.84 (0.16)	2.51 (0.51)
20.00	2.42 (0.35)	2.01 (0.22)	2.71 (0.57)
25.00	2.66 (0.33)	2.15 (0.22)	2.87 (0.56)
50.00	3.29 (0.39)	2.52 (0.20)	3.43 (0.60)
100.00	3.95 (0.61)	2.76 (0.19)	4.10 (0.80)
150.00	4.31 (0.71)	2.92 (0.23)	4.43 (0.94)
200.00	4.50 (0.81)	3.00 (0.28)	4.63 (1.09)
500.00	5.30 (1.37)	3.62 (0.28)	5.74 (1.65)

SOUTH CAROLINA STATION 17 Upper Stono River

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	, EXTROPIC (SD)	, COMBINED (SD)
2.00	1.24 (0.00)	1.24 (0.00)	1.24 (0.00)
5.00	1.24 (0.00)	1.69 (0.03)	1.85 (0.22)
10.00	1.64 (0.48)	1.88 (0.08)	2.58 (0.56)
15.00	2.35 (0.43)	2.13 (0.25)	3.04 (0.68)
20.00	2.77 (0.41)	2.41 (0.35)	3.31 (0.76)
25.00	3.07 (0.38)	2.64 (0.37)	3.48 (0.75)
50.00	3.77 (0.43)	3.24 (0.32)	4.03 (0.75)
100.00	4.45 (0.71)	3.59 (0.29)	4.69 (1.00)
150.00	4.88 (0.82)	3.86 (0.37)	5.06 (1.20)
200.00	5.10 (0.94)	4.00 (0.45)	5.31 (1.39)
500.00	6.14 (1.63)	4.59 (0.46)	6.79 (2.08)

SOUTH CAROLINA STATION 18 Ashley River

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	, EXTROPIC (SD)	, COMBINED (SD)
2.00	1.21 (0.00)	1.21 (0.00)	1.21 (0.00)
5.00	1.21 (0.00)	1.72 (0.03)	1.83 (0.21)
10.00	1.45 (0.46)	1.88 (0.09)	2.43 (0.55)
15.00	2.13 (0.44)	2.08 (0.22)	2.87 (0.65)
20.00	2.60 (0.43)	2.31 (0.31)	3.14 (0.74)
25.00	2.88 (0.45)	2.54 (0.32)	3.31 (0.77)
50.00	3.68 (0.51)	3.07 (0.27)	3.91 (0.78)
100.00	4.42 (0.68)	3.37 (0.26)	4.63 (0.94)
150.00	4.89 (0.83)	3.60 (0.32)	5.06 (1.15)
200.00	5.13 (0.95)	3.72 (0.38)	5.32 (1.33)
500.00	6.26 (1.65)	4.31 (0.39)	6.85 (2.04)

SOUTH CAROLINA STATION 19 Stono River

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.17 (0.00)	1.17 (0.00)	1.17 (0.00)
5.00	1.17 (0.00)	1.49 (0.03)	1.54 (0.17)
10.00	1.17 (0.00)	1.59 (0.04)	1.85 (0.35)
15.00	1.55 (0.30)	1.71 (0.11)	2.15 (0.41)
20.00	1.86 (0.31)	1.85 (0.19)	2.35 (0.50)
25.00	2.10 (0.32)	1.98 (0.20)	2.48 (0.52)
50.00	2.80 (0.43)	2.32 (0.17)	2.93 (0.60)
100.00	3.45 (0.58)	2.52 (0.17)	3.56 (0.75)
150.00	3.84 (0.69)	2.66 (0.20)	3.93 (0.90)
200.00	4.04 (0.80)	2.73 (0.24)	4.13 (1.04)
500.00	4.98 (1.42)	3.04 (0.24)	5.27 (1.66)

SOUTH CAROLINA STATION 20 Cooper River

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.21 (0.00)	1.21 (0.00)	1.21 (0.00)
5.00	1.21 (0.00)	1.66 (0.03)	1.78 (0.21)
10.00	1.45 (0.43)	1.82 (0.08)	2.38 (0.51)
15.00	2.13 (0.42)	2.02 (0.21)	2.80 (0.63)
20.00	2.57 (0.40)	2.25 (0.30)	3.04 (0.70)
25.00	2.84 (0.43)	2.45 (0.30)	3.21 (0.73)
50.00	3.59 (0.48)	2.95 (0.27)	3.80 (0.75)
100.00	4.30 (0.67)	3.25 (0.25)	4.50 (0.91)
150.00	4.75 (0.79)	3.47 (0.31)	4.91 (1.10)
200.00	4.97 (0.91)	3.58 (0.38)	5.15 (1.29)
500.00	6.01 (1.50)	4.18 (0.38)	6.58 (1.87)

SOUTH CAROLINA STATION 21 Charleston Inner Ha

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.18 (0.00)	1.18 (0.00)	1.18 (0.00)
5.00	1.18 (0.00)	1.59 (0.03)	1.65 (0.15)
10.00	1.18 (0.00)	1.70 (0.05)	2.04 (0.38)
15.00	1.71 (0.34)	1.84 (0.16)	2.41 (0.50)
20.00	2.07 (0.40)	2.03 (0.24)	2.63 (0.63)
25.00	2.38 (0.40)	2.18 (0.25)	2.79 (0.64)
50.00	3.27 (0.55)	2.58 (0.22)	3.45 (0.77)
100.00	4.04 (0.66)	2.83 (0.20)	4.22 (0.86)
150.00	4.50 (0.84)	3.00 (0.24)	4.65 (1.09)
200.00	4.74 (0.98)	3.09 (0.29)	4.89 (1.28)
500.00	5.82 (1.80)	3.67 (0.29)	6.33 (2.10)

SOUTH CAROLINA STATION 22 Wando River

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	, EXTROPIC (SD)	, COMBINED (SD)
2.00	1.22 (0.00)	1.22 (0.00)	1.22 (0.00)
5.00	1.22 (0.00)	1.58 (0.03)	1.68 (0.16)
10.00	1.29 (0.43)	1.73 (0.06)	2.20 (0.49)
15.00	1.94 (0.40)	1.91 (0.19)	2.59 (0.60)
20.00	2.31 (0.40)	2.13 (0.28)	2.82 (0.68)
25.00	2.59 (0.39)	2.31 (0.28)	2.97 (0.68)
50.00	3.27 (0.44)	2.78 (0.25)	3.49 (0.69)
100.00	3.95 (0.63)	3.06 (0.23)	4.16 (0.86)
150.00	4.37 (0.73)	3.27 (0.29)	4.53 (1.02)
200.00	4.58 (0.84)	3.37 (0.35)	4.76 (1.19)
500.00	5.57 (1.41)	3.97 (0.35)	6.16 (1.76)

SOUTH CAROLINA STATION 23 Charleston Harbor

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	, EXTROPIC (SD)	, COMBINED (SD)
2.00	1.15 (0.00)	1.15 (0.00)	1.15 (0.00)
5.00	1.15 (0.00)	1.50 (0.03)	1.55 (0.15)
10.00	1.15 (0.00)	1.60 (0.06)	1.87 (0.37)
15.00	1.54 (0.30)	1.72 (0.13)	2.17 (0.44)
20.00	1.87 (0.35)	1.87 (0.18)	2.35 (0.53)
25.00	2.14 (0.36)	1.98 (0.19)	2.49 (0.55)
50.00	2.97 (0.51)	2.30 (0.18)	3.08 (0.69)
100.00	3.66 (0.61)	2.51 (0.16)	3.76 (0.77)
150.00	4.09 (0.77)	2.64 (0.20)	4.17 (0.97)
200.00	4.31 (0.89)	2.71 (0.23)	4.39 (1.13)
500.00	5.32 (1.64)	2.98 (0.24)	5.59 (1.88)

SOUTH CAROLINA STATION 24 Dewees Inlet

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	, EXTROPIC (SD)	, COMBINED (SD)
2.00	1.10 (0.00)	1.10 (0.00)	1.10 (0.00)
5.00	1.10 (0.00)	1.49 (0.03)	1.56 (0.17)
10.00	1.10 (0.00)	1.60 (0.04)	1.84 (0.39)
15.00	1.58 (0.35)	1.70 (0.10)	2.12 (0.45)
20.00	1.91 (0.35)	1.82 (0.15)	2.29 (0.50)
25.00	2.17 (0.36)	1.91 (0.16)	2.44 (0.52)
50.00	2.96 (0.46)	2.19 (0.17)	3.04 (0.62)
100.00	3.61 (0.61)	2.41 (0.16)	3.70 (0.78)
150.00	4.03 (0.75)	2.53 (0.19)	4.11 (0.93)
200.00	4.25 (0.86)	2.60 (0.21)	4.32 (1.08)
500.00	5.23 (1.43)	2.91 (0.21)	5.48 (1.64)

SOUTH CAROLINA STATION 25 Bulls Bay

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.09 (0.00)	1.09 (0.00)	1.09 (0.00)
5.00	1.09 (0.00)	1.49 (0.04)	1.61 (0.28)
10.00	1.44 (0.35)	1.64 (0.06)	2.04 (0.41)
15.00	2.01 (0.34)	1.76 (0.11)	2.35 (0.45)
20.00	2.37 (0.35)	1.89 (0.15)	2.57 (0.50)
25.00	2.63 (0.35)	1.98 (0.17)	2.74 (0.52)
50.00	3.32 (0.42)	2.27 (0.17)	3.42 (0.59)
100.00	3.98 (0.59)	2.50 (0.17)	4.11 (0.77)
150.00	4.39 (0.73)	2.64 (0.20)	4.51 (0.93)
200.00	4.61 (0.84)	2.71 (0.23)	4.73 (1.07)
500.00	5.59 (1.40)	3.30 (0.23)	6.02 (1.64)

SOUTH CAROLINA STATION 26 Cape Romain Refuge

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	0.68 (0.00)	0.68 (0.00)	0.68 (0.00)
5.00	0.68 (0.00)	1.38 (0.05)	1.44 (0.24)
10.00	1.16 (0.36)	1.46 (0.04)	1.71 (0.39)
15.00	1.77 (0.34)	1.54 (0.06)	1.94 (0.40)
20.00	2.11 (0.32)	1.60 (0.07)	2.18 (0.39)
25.00	2.38 (0.33)	1.65 (0.08)	2.43 (0.40)
50.00	3.11 (0.44)	1.79 (0.09)	3.16 (0.53)
100.00	3.86 (0.66)	1.93 (0.11)	3.92 (0.77)
150.00	4.28 (0.80)	2.01 (0.13)	4.33 (0.93)
200.00	4.49 (0.92)	2.05 (0.15)	4.54 (1.06)
500.00	5.46 (1.59)	2.39 (0.15)	5.64 (1.73)

SOUTH CAROLINA STATION 27 Sampit River

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	0.47 (0.00)	0.47 (0.00)	0.47 (0.00)
5.00	0.47 (0.00)	1.21 (0.04)	1.53 (0.40)
10.00	1.71 (0.44)	1.49 (0.07)	1.94 (0.50)
15.00	2.47 (0.47)	1.60 (0.05)	2.51 (0.52)
20.00	2.85 (0.36)	1.65 (0.06)	2.87 (0.42)
25.00	3.05 (0.31)	1.68 (0.07)	3.07 (0.38)
50.00	3.58 (0.37)	1.81 (0.09)	3.62 (0.47)
100.00	4.27 (0.59)	1.96 (0.13)	4.31 (0.72)
150.00	4.61 (0.66)	2.05 (0.15)	4.65 (0.81)
200.00	4.78 (0.74)	2.10 (0.17)	4.82 (0.91)
500.00	5.58 (1.21)	2.39 (0.18)	5.73 (1.39)

SOUTH CAROLINA STATION 28 South Santee

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	, EXTROPIC (SD)	, COMBINED (SD)
2.00	1.05 (0.00)	1.05 (0.00)	1.05 (0.00)
5.00	1.05 (0.00)	1.34 (0.04)	1.42 (0.19)
10.00	1.06 (0.31)	1.44 (0.02)	1.55 (0.34)
15.00	1.56 (0.27)	1.48 (0.03)	1.69 (0.30)
20.00	1.86 (0.27)	1.51 (0.03)	1.91 (0.30)
25.00	2.07 (0.30)	1.53 (0.03)	2.11 (0.34)
50.00	2.71 (0.39)	1.59 (0.05)	2.76 (0.43)
100.00	3.30 (0.57)	1.65 (0.06)	3.36 (0.63)
150.00	3.70 (0.69)	1.70 (0.08)	3.75 (0.77)
200.00	3.90 (0.79)	1.73 (0.09)	3.95 (0.88)
500.00	4.82 (1.33)	2.07 (0.09)	5.01 (1.42)

SOUTH CAROLINA STATION 29 North Santee

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	, EXTROPIC (SD)	, COMBINED (SD)
2.00	1.06 (0.00)	1.06 (0.00)	1.06 (0.00)
5.00	1.06 (0.00)	1.33 (0.04)	1.41 (0.20)
10.00	1.08 (0.30)	1.42 (0.02)	1.51 (0.32)
15.00	1.57 (0.26)	1.45 (0.02)	1.65 (0.29)
20.00	1.86 (0.25)	1.47 (0.03)	1.86 (0.28)
25.00	2.08 (0.29)	1.49 (0.03)	2.09 (0.32)
50.00	2.69 (0.37)	1.54 (0.04)	2.69 (0.41)
100.00	3.24 (0.55)	1.60 (0.04)	3.24 (0.59)
150.00	3.62 (0.65)	1.63 (0.06)	3.62 (0.71)
200.00	3.81 (0.75)	1.64 (0.06)	3.81 (0.81)
500.00	4.66 (1.29)	1.68 (0.07)	4.68 (1.36)

SOUTH CAROLINA STATION 30 Black River

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	, EXTROPIC (SD)	, COMBINED (SD)
2.00	0.50 (0.00)	0.50 (0.00)	0.50 (0.00)
5.00	0.50 (0.00)	1.18 (0.06)	1.65 (0.47)
10.00	2.15 (0.37)	1.51 (0.10)	2.33 (0.47)
15.00	2.85 (0.44)	1.69 (0.11)	2.89 (0.55)
20.00	3.31 (0.44)	1.81 (0.11)	3.34 (0.55)
25.00	3.60 (0.40)	1.89 (0.12)	3.62 (0.52)
50.00	4.12 (0.26)	2.11 (0.13)	4.14 (0.39)
100.00	4.44 (0.28)	2.29 (0.17)	4.47 (0.46)
150.00	4.65 (0.35)	2.40 (0.18)	4.68 (0.53)
200.00	4.76 (0.41)	2.46 (0.20)	4.78 (0.61)
500.00	5.26 (0.75)	2.74 (0.20)	5.36 (0.95)

SOUTH CAROLINA STATION 31 Winyah Bay

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.07 (0.00)	1.07 (0.00)	1.07 (0.00)
5.00	1.07 (0.00)	1.39 (0.03)	1.46 (0.17)
10.00	1.07 (0.00)	1.48 (0.01)	1.54 (0.31)
15.00	1.46 (0.25)	1.51 (0.01)	1.64 (0.27)
20.00	1.74 (0.26)	1.53 (0.02)	1.77 (0.28)
25.00	1.98 (0.31)	1.54 (0.03)	1.99 (0.34)
50.00	2.66 (0.41)	1.59 (0.04)	2.66 (0.44)
100.00	3.30 (0.59)	1.65 (0.04)	3.30 (0.63)
150.00	3.73 (0.74)	1.68 (0.05)	3.74 (0.80)
200.00	3.95 (0.87)	1.70 (0.06)	3.95 (0.93)
500.00	4.96 (1.54)	1.70 (0.06)	4.98 (1.59)

SOUTH CAROLINA STATION 32 North Inlet

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.14 (0.00)	1.14 (0.00)	1.14 (0.00)
5.00	1.14 (0.00)	1.57 (0.03)	1.65 (0.21)
10.00	1.14 (0.32)	1.68 (0.02)	1.75 (0.34)
15.00	1.67 (0.30)	1.71 (0.02)	1.87 (0.32)
20.00	2.03 (0.32)	1.73 (0.02)	2.09 (0.35)
25.00	2.26 (0.38)	1.75 (0.03)	2.31 (0.41)
50.00	3.10 (0.50)	1.81 (0.04)	3.15 (0.55)
100.00	3.88 (0.68)	1.87 (0.05)	3.94 (0.73)
150.00	4.34 (0.85)	1.91 (0.06)	4.39 (0.91)
200.00	4.57 (0.98)	1.94 (0.07)	4.62 (1.06)
500.00	5.68 (1.67)	2.22 (0.08)	5.87 (1.74)

SOUTH CAROLINA STATION 33 Waccamaw River

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	0.51 (0.00)	0.51 (0.00)	0.51 (0.00)
5.00	0.51 (0.00)	1.03 (0.06)	1.61 (0.46)
10.00	2.28 (0.30)	1.36 (0.12)	2.42 (0.42)
15.00	2.77 (0.30)	1.61 (0.14)	2.81 (0.44)
20.00	3.13 (0.36)	1.77 (0.14)	3.17 (0.50)
25.00	3.41 (0.40)	1.89 (0.15)	3.44 (0.55)
50.00	4.18 (0.45)	2.18 (0.17)	4.20 (0.61)
100.00	4.71 (0.43)	2.42 (0.19)	4.75 (0.62)
150.00	5.00 (0.43)	2.56 (0.21)	5.03 (0.64)
200.00	5.15 (0.49)	2.63 (0.23)	5.18 (0.71)
500.00	5.84 (0.84)	2.91 (0.23)	5.97 (1.07)

SOUTH CAROLINA STATION 34 Pawleys Inlet

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.15 (0.00)	1.15 (0.00)	1.15 (0.00)
5.00	1.15 (0.00)	1.56 (0.03)	1.65 (0.22)
10.00	1.20 (0.33)	1.68 (0.03)	1.79 (0.36)
15.00	1.75 (0.35)	1.73 (0.03)	1.93 (0.38)
20.00	2.11 (0.36)	1.75 (0.03)	2.13 (0.39)
25.00	2.39 (0.43)	1.77 (0.03)	2.40 (0.46)
50.00	3.17 (0.51)	1.84 (0.04)	3.18 (0.55)
100.00	3.96 (0.68)	1.92 (0.06)	3.96 (0.74)
150.00	4.44 (0.84)	1.96 (0.08)	4.45 (0.91)
200.00	4.69 (0.97)	1.98 (0.09)	4.70 (1.06)
500.00	5.82 (1.61)	2.07 (0.10)	5.84 (1.71)

SOUTH CAROLINA STATION 35 Midway Inlet

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.16 (0.00)	1.16 (0.00)	1.16 (0.00)
5.00	1.16 (0.00)	1.55 (0.02)	1.64 (0.22)
10.00	1.23 (0.34)	1.67 (0.03)	1.80 (0.37)
15.00	1.79 (0.35)	1.72 (0.03)	1.96 (0.38)
20.00	2.15 (0.37)	1.76 (0.03)	2.16 (0.40)
25.00	2.44 (0.41)	1.78 (0.04)	2.44 (0.45)
50.00	3.19 (0.49)	1.85 (0.04)	3.19 (0.54)
100.00	3.94 (0.65)	1.94 (0.07)	3.94 (0.72)
150.00	4.41 (0.80)	1.99 (0.09)	4.42 (0.89)
200.00	4.65 (0.93)	2.01 (0.10)	4.66 (1.03)
500.00	5.74 (1.55)	2.07 (0.11)	5.76 (1.66)

SOUTH CAROLINA STATION 36 Murells Inlet

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	EXTROPIC (SD)	COMBINED (SD)
2.00	1.18 (0.00)	1.18 (0.00)	1.18 (0.00)
5.00	1.18 (0.00)	1.51 (0.02)	1.60 (0.22)
10.00	1.24 (0.34)	1.63 (0.03)	1.79 (0.37)
15.00	1.80 (0.35)	1.69 (0.04)	1.97 (0.39)
20.00	2.16 (0.36)	1.73 (0.04)	2.17 (0.40)
25.00	2.42 (0.38)	1.76 (0.04)	2.43 (0.42)
50.00	3.13 (0.45)	1.84 (0.05)	3.14 (0.50)
100.00	3.83 (0.61)	1.93 (0.07)	3.83 (0.68)
150.00	4.27 (0.74)	1.99 (0.09)	4.28 (0.83)
200.00	4.50 (0.86)	2.01 (0.11)	4.50 (0.97)
500.00	5.53 (1.43)	2.10 (0.12)	5.55 (1.55)

SOUTH CAROLINA STATION 37 AIWW Horry County

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	, EXTROPIC (SD)	, COMBINED (SD)
2.00	1.20 (0.00)	1.20 (0.00)	1.20 (0.00)
5.00	1.20 (0.00)	1.45 (0.03)	1.58 (0.23)
10.00	1.47 (0.41)	1.60 (0.03)	1.85 (0.45)
15.00	2.05 (0.37)	1.68 (0.04)	2.09 (0.41)
20.00	2.42 (0.33)	1.73 (0.05)	2.43 (0.37)
25.00	2.67 (0.31)	1.77 (0.05)	2.68 (0.36)
50.00	3.26 (0.34)	1.87 (0.06)	3.27 (0.40)
100.00	3.85 (0.54)	1.96 (0.08)	3.86 (0.62)
150.00	4.21 (0.62)	2.03 (0.10)	4.21 (0.72)
200.00	4.39 (0.70)	2.05 (0.11)	4.39 (0.82)
500.00	5.22 (1.20)	2.08 (0.12)	5.23 (1.32)

SOUTH CAROLINA STATION 38 Little River

RETURN PERIOD - YRS - SURGE (M)	TROPICAL (SD)	, EXTROPIC (SD)	, COMBINED (SD)
2.00	1.18 (0.00)	1.18 (0.00)	1.18 (0.00)
5.00	1.18 (0.00)	1.35 (0.03)	1.46 (0.19)
10.00	1.37 (0.40)	1.47 (0.03)	1.69 (0.42)
15.00	1.93 (0.35)	1.53 (0.03)	1.94 (0.38)
20.00	2.25 (0.32)	1.57 (0.04)	2.25 (0.36)
25.00	2.49 (0.29)	1.60 (0.04)	2.49 (0.33)
50.00	3.01 (0.31)	1.68 (0.05)	3.01 (0.35)
100.00	3.53 (0.49)	1.76 (0.06)	3.54 (0.55)
150.00	3.87 (0.57)	1.80 (0.07)	3.88 (0.64)
200.00	4.04 (0.65)	1.82 (0.08)	4.05 (0.73)
500.00	4.83 (1.13)	1.88 (0.08)	4.85 (1.21)

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13. ABSTRACT *(Maximum 200 words)*

This report describes procedures followed and results obtained for a frequency analysis of storm-generated water levels along the open coast and up the major tributaries of South Carolina. In the study, tropical and extratropical storm events that have historically impacted South Carolina are simulated using the long-wave hydrodynamic model ADCIRC. The resulting storm surge elevations with corresponding tides are input to the Empirical Simulation Technique (EST) life-cycle stochastic model. Life-cycle simulations are postprocessed to generate storm surge frequency-of-occurrence relationships for 38 selected locations within the study area.

14. SUBJECT TERMS

Empirical Simulation Technique	Numerical modeling
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